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DEPARTMENT OF THE INTERIOR
CANADA

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Deputy Minister.



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Frontispiece Observatory from South.

DEPARTMENT OF THE INTERIOR
CANADA

Hon. ARTHUR MEIGHEN, Minister; W. W. CORY, C.M.G., Deputy Minister.

PUBLICATIONS

OF THE

Dominion Astrophysical Observatory

Victoria, B. C.

J. S. PLASKETT, Director

Vol. I, No. 1

DESCRIPTION OF BUILDING AND EQUIPMENT

BY

J. S. PLASKETT



OTTAWA

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DESCRIPTION OF BUILDING AND EQUIPMENT

By J. S. PLASKETT, Director

CHAPTER I INTRODUCTION

It has seemed desirable before describing the installation, to give some account of the initiation and development of the undertaking, as only when the methods of development are brought out will the account be complete and the description thoroughly understood.

In the development of the radial velocity work by the writer at the Dominion Astronomical Observatory, Ottawa, a stage was reached where it was recognized that the field of useful work with so comparatively small an aperture as 15 inches would soon be seriously limited. Even with single prism dispersion, 33 Å per millimetre at $H\gamma$, stars fainter than 5.5 photographic magnitude required impracticable exposure times and furthermore it was deemed inadvisable to observe, with such low dispersion, stars with good lines, when much more accurate values could be obtained with greater dispersion. Thus the field was limited to spectroscopic binaries of early type, brighter than 5.5 magnitude and it was evident that, with a telescope of 15-inch aperture, the available stars for observation would soon be exhausted.

Hence, when the need for larger telescopic aperture made itself felt, it was natural to be on the lookout for opportunity to secure it. Plans for such additional equipment began to take more concrete shape at the Mt. Wilson meeting of the International Union for Co-operation in Solar Research in 1910, which I had the good fortune and honour to attend as representative of the Dominion Astronomical Observatory.

At the meeting a committee on Co-operation in the Determination of Stellar Radial Velocities of which Professor W. W. Campbell, Director of the Lick Observatory, was chairman met and discussed the needs in radial velocity work and the resources available for meeting these needs. It was evident that only the 36-inch telescope at the Lick Observatory and part of the time of the 60-inch at Mt. Wilson could be devoted to this work and further equipment was urgently needed if substantial progress in this important work was to be obtained.

At the same time, the great success of the 60-inch reflector at Mt. Wilson, made it practically certain that a large reflecting telescope could successfully carry on radial velocity observations at least equally as well as a refractor of the same aperture and at one-fourth the initial cost, leaving out of consideration the impossibility of obtaining suitable material for the objective of a very large refractor.

As a consequence of these two considerations, I determined to use every possible effort towards obtaining a large reflecting telescope for the Dominion Astronomical Observatory, at least of 60-inch aperture, and if possible larger. Upon returning to Ottawa, I brought the matter to the attention of the Chief Astronomer, Dr. W. F. King, and, as in all attempts to increase the scope and usefulness of the work of the observatory, I found him most sympathetic and eager to advance the project by all means in his power. I can not refrain in this connection from paying a sincere tribute to his memory. No man could have a chief more considerate, more encouraging, more helpful in every way, and more willing and eager to see his staff make progress than I and all the observatory staff had in Dr. King, and his death was a great loss to the Astronomical Branch, to Canada and to the scientific world.

Nothing definite, however, was attempted at that time and it was not until the meeting of the Astronomical and Astrophysical Society of America, which was held in Ottawa in August, 1911, that the first step towards the initiation of the undertaking was made. When the report of the Committee on Co-operation in Radial Velocities was presented by me at the chairman's request, the question of further equipment for the carrying on of the work was introduced, and the President of the Society, Prof. E. C. Pickering, expressed a hope that the Government could be persuaded to provide a large telescope. Later a resolution was passed expressing the admiration of the society for the radial velocity work accomplished with the 15-inch telescope and expressing the hope that the Government would soon provide a larger telescope.

This resolution was transmitted to the then Minister of the Interior, the Hon. Frank Oliver, but, as this was just previous to the election of 1911, naturally no action was taken at that time. Further, owing to the change of Government and to further change of ministers in the Department of the Interior, from the Hon. Robert Rogers to the Hon. Dr. Roche, the resolution had become pigeon-holed and I felt that if anything was to be accomplished, the matter would have to be brought anew to the attention of the Government.

A suitable occasion arose at the meeting of the Royal Society of Canada in May, 1912, when a resolution was introduced in Section III (Mathematical, Physical and Chemical Sciences) and was passed at a general meeting of the society, instructing the council to prepare a memorial to the Government urging the providing of a large reflecting telescope for the extension of the radial velocity work of the observatory.

This memorial, accompanied by strong letters of commendation of the project from the most eminent astronomers of Europe and America, was presented to the Premier in July, 1912, on the eve of his departure for England, was very sympathetically received by him, and was presumably transmitted to the Hon. Dr. Roche, Minister of the Interior.

However, no action was taken at the time and it almost looked as if it would again be allowed to lapse. I am convinced from the support he gave later that the minister was favourably inclined towards the project, but did not wish to commit himself without feeling sure of definite support from his colleagues and fellow members. It seemed necessary, therefore, if the telescope was to be obtained, to interest members of Parliament and members of the Cabinet in the project sufficiently to have them urge its authorization on the minister. This work, I, with the help of Dr. King, undertook and finally a

voluntary committee of several members of Parliament, headed by Sir Edmund Osler, with F. H. Shepherd as organizer, interviewed the Hon. Dr. Roche on Feb. 12, 1913, and obtained his consent to make enquiries and obtain tenders for the construction of the telescope. My thanks and those of all interested in the advance of astronomy are due to Sir Edmund Osler, Mr. Shepherd, Mr. Arthur Meighen, and the other members of the committee for their active interest and help in this matter. I have also pleasure in expressing my appreciation of the sympathy and active help of members of the Cabinet and especially of the Hon. Martin Burrell in bringing this matter to a successful conclusion. Without such support, it is unlikely the construction would have been authorized, and this considerable accession to the existing resources for astronomical research of the world would have been indefinitely postponed.

CHAPTER II—ENQUIRIES, SPECIFICATIONS AND TENDERS.

The first authorization of the minister was to make enquiries, prepare specifications and call for tenders for the telescope and the proposal was to get tenders for two sizes of instrument with apertures 60-inch and 72-inch.

Pursuant to this authority, I was deputed by Dr. King to visit the larger observatories, especially those where reflecting telescopes had been or were used, and the principal manufacturers of the optical parts and mountings of large telescopes in the United States. Afterwards, as the International Union for Co-operation in Solar Research was to hold a meeting at Bonn in August, 1913, and, as the Dominion Observatory, Ottawa, had taken part in the programme for the spectroscopic determination of the solar rotation as well as in other features of the work of the union, it was proposed to attend this important conference and at the same time to obtain further information in regard to the design of the telescope and to consult with some of the manufacturers in Europe.

Consequently, early in March, 1913, I departed from Ottawa to visit the Pacific Coast observatories at Mt. Hamilton and Mt. Wilson, and at the same time to make preliminary enquiries at Medicine Hat, Okanagan and Victoria in regard to the most suitable location for the telescope. Visiting the Lick Observatory in the first place I was most kindly received by Director Campbell and the members of his staff and every facility was offered me and all information, that might be of service, given. Their experience with the 36-inch reflectors at Mt. Hamilton and at Santiago de Chile was most valuable and many very useful ideas were obtained and noted for the design of the proposed telescope. So far as the design of the mounting was concerned, they favoured the long polar axis between separate piers with the declination axis crossing it in an intermediate position. The 36-inch Crossley is mounted in a modification of this form and gives good satisfaction.

From the Lick Observatory I travelled to Pasadena and here at the offices and on Mt. Wilson at the Solar Observatory I found every one most willing to help in any possible way, and many valuable ideas for the design of the reflector were obtained here. The great success of the 60-inch reflector, and their experience in the operation of this large instrument, naturally made their suggestions most valuable both as to what should be

incorporated and what avoided in the design of large reflecting telescopes. As is well known, in the 60-inch mounting the tube swings in a huge fork on the north end of the polar axis and in the 100-inch centrally between the two sides of a long bifurcated polar axis. In the case of the 60-inch, owing to interference of the tube with the mercury float, low declinations cannot be reached, while with the 100-inch the forked polar axis prevents the telescope tube from reaching a circle of about 30° radius around the pole. While such limitations are not very serious, especially where as in this case there are two large telescopes which supplement one another, yet in the design of the Canadian telescope it was deemed desirable, other things being equal, to have it mounted so as to reach the whole of the sky available at this latitude. As this is readily obtained by a type similar to the Crossley, Ann Arbor or Melbourne mountings, the Mt. Wilson forms were not seriously considered, although they have advantages in their symmetrical form, in the fact that the axis of the tube intersecting the polar axis lightens considerably the weight of the moving parts and requires a somewhat smaller dome than when the tube is mounted eccentrically. At the Detroit Observatory, Ann Arbor, where is a $37\frac{1}{2}$ -inch reflector of quite recent construction, I also obtained useful assistance in many details of construction, and am indebted to Dr. Curtiss for his willingness to assist in every possible way.

The Harvard Observatory was visited and I was much interested in the novel and original way the mounting of the 60-inch Common telescope was being carried out and in their method of synchronized electrical driving in the place of the regular governor type employed in most telescope driving clocks. Director Pickering was most kind and eager to give assistance in preparing specifications to give the best results.

Finally the works of the Warner & Swasey Co. of Cleveland and of the J. A. Brashear Co. of Pittsburgh were visited and further information of a very valuable character in regard to the mechanical and optical details of the proposed telescope were obtained.

This mass of information, much of it of course contradictory, was then arranged and tabulated and I set myself the task of preparing specifications from which competitive tenders could be obtained. In these specifications the purpose was to set forth the general form of the mounting and optical parts, the essential operations to be performed with suggestions as to the means, and the character of the workmanship required, but at the same time to leave the makers of the instrument full scope for the exercise of their ingenuity and experience in working out the details of the mechanism.

In deciding between opposing opinions in regard to the best practice optically or mechanically, especially in the latter, I was possibly better equipped than most astronomers owing to my mechanical training and knowledge and I venture to think that owing to this training the telescope is a better instrument than would have otherwise been the case.

It has seemed desirable to insert here the specifications sent to the competing firms, as indicating what I considered the best practice before the telescope was designed and in the hope that they may possibly be of use to others. As will be noticed when the description is given, these specifications were altered in a few details but generally speaking were fairly closely adhered to, and were sufficiently definite to enable tenderers to closely calculate the cost of the completed instrument and hence give an equal chance to all.

It will be noticed that these specifications contain little radical or different from the conventional form of telescope. It did not seem to be wise in a large instrument like this to introduce any untried features unless with a surety of improvement, and although I was urged to adopt some rather startling modifications, such as the use of a synchronized electric motor instead of the usual governor drive, I did not think it advisable to depart from the entirely satisfactory present methods to one which did not offer any striking advantages and did not seem to me so certain and reliable. There is one feature, however, in the design for which I am responsible, and that is the substitution of plain ball or roller bearings in the bearings of polar and declination axes, in the place of using cylindrical bearings to maintain collimation and relieving part of the friction on these by rollers or by mercury flotation. The ball or roller races in modern anti-friction bearings are of the highest quality, are hardened and ground by the best machinery and are finished to such a high degree of accuracy and polish as to excel the best of the old type cylindrical bearings so far as maintaining accuracy of collimation is concerned. At the same time the friction is very much reduced, probably to about one-fifth of the old type roller relieved cylindrical bearing, and also, I believe, below that given by mercury flotation methods, which have the disadvantage of being cumbrous, expensive and messy. Results of the tests on the bearings of the 72-inch telescope will be given in the description of the mounting.

SPECIFICATIONS FOR LARGE REFLECTING TELESCOPE FOR DOMINION ASTROPHYSICAL OBSERVATORY

PRELIMINARY

1. Estimates shall be given to cover complete telescopes of apertures 60 and 72 inches. The division of the cost between optical parts and mounting shall be indicated.
2. It shall be distinctly understood that material and workmanship are to be strictly first class.
3. The specifications following are intended to cover only the general features of the instrument. Any modification of the form proposed herein will be carefully considered and if deemed of advantage adopted. When the contract is awarded all matters of detail, design and construction are to be submitted to the representative of the Government for approval, and a copy of the final drawings to be furnished.
4. It is desirable that any estimates submitted be accompanied by preliminary drawings or sketches approximately to scale showing the proposed form and principal features of the mounting accompanied by any description and specification that may be necessary to explain the design.

GENERAL SPECIFICATIONS

1. The main principle to be borne in mind in designing this telescope is to have an instrument convenient in operation, smooth and satisfactory in running without unnecessary complications.
2. The telescope is primarily intended to be used for spectrographic observations in the Cassegrain form. For this purpose a hole is required in the mirror, the spectrograph being attached below the cell.

3. The telescope in addition must be capable of being used for direct photography at the focus of the principal mirror, both at the side of the tube by the use of a Newtonian flat and directly in the prime focus.

4. A third possible use of the reflector would be with a small and comparatively light spectrograph in the prime focus.

5. Further it may be desirable to obtain direct photographs at the Cassegrain focus. If the hole in the principal mirror can be made 10 or 12 inches in diameter no additional attachment will be necessary, but if it is not considered desirable to attempt a hole of larger diameter than two or three inches then provision shall be made, in the lower section of the tube, for attaching webs to hold a diagonal mirror to reflect the light to a 10-inch square plate at the side, though such an attachment is not to be furnished at present.

OPTICAL PARTS

1. The principal and secondary mirrors shall be cast of the material, hard crown, found most suitable and generally used for large mirrors. All the mirrors must be of material free from large visible defects and must be thoroughly and carefully annealed so as to be as free as possible from internal strains.

2. The ratio of thickness to diameter in the principal mirror shall be not less than one to eight, in the smaller mirrors not less than one to six. The principal mirror shall have a central hole cast in it whose diameter is dependent upon conditions. If the diameter can be safely made about one-sixth the whole diameter, a third reflection for direct photography in the Cassegrain focus will be avoided. But if it is considered that a large hole would entail greater danger of non-uniformity of internal structure or would considerably weaken the mirror then the size of the hole to be cast may be diminished to about two inches which may be later enlarged by grinding to three inches, which is sufficient for spectrographic work.

3. The ratio of aperture to focal length for the parabolic mirror shall be one to five; for the Cassegrain combination one to eighteen. The diameter of the Cassegrain secondary shall be about 19 inches and its radius of curvature about 19.5 feet, while it shall be placed about 7 feet from the principal focus of a 72-inch mirror. For a 60-inch mirror the dimensions will be proportionately reduced. The Newtonian flat for a 72-inch mirror should be elliptical in shape with the apertures of major and minor axes about 20 and 14 inches respectively.

4. All the mirrors shall be ground smooth and true on the periphery, also around the central hole in the main mirror, and shall be ground and polished approximately flat on the back.

5. After the main mirror has been ground approximately to shape it would be desirable for it to stand for some time before figuring and if possible without delaying the completion of the telescope this should be arranged for.

6. All the optical surfaces shall be of the highest quality both as respects figure and polish. They shall be free from zonal errors and from astigmatism and when tested by the Foucault or knife edge method shall show perfectly smooth and uniform figures.

7. The main paraboloidal surface is to be tested both at the centre of curvature and at the principal focus. In the former case, with the artificial star fixed in position

the centre of focus for zones of different radii shall not vary from the theoretically computed value to a greater extent than $\frac{1}{200}$ inch for the outer zones and $\frac{1}{100}$ for the inner zones. When tested at the principal focus by means of an accurate auxiliary plane the extreme difference in focus with a fixed artificial star for zones a foot from the edge shall not exceed $\frac{1}{400}$ inch and for the inner zones $\frac{1}{200}$ inch. The same conditions shall be true when the Newtonian is tested in conjunction with the main mirror.

8. The Cassegrain secondary shall be tested in conjunction with the paraboloid and auxiliary plane and the differences of focus allowable, in the images from different zones shall not exceed $\frac{1}{100}$ inch. If found desirable after the instrument is installed the secondary may be further figured to improve average conditions. The optician shall be ready to do this work without additional charge although his travelling and living expenses will be paid.

9. The diameter of the auxiliary plane used in testing the principal mirror shall be at least three-quarters the diameter of the latter and shall be corrected with the highest possible precision. It and the sphere with which it is tested shall be required to be free from zonal errors and from differences of focus for different zones of any measurable or observable amount.

10. The optician shall provide an approved knife edge apparatus for making these tests. The artificial star shall be formed by condensing the light of a powerful source, the electric arc if necessary, on a small hole not exceeding .002 inch in diameter. This star shall be capable of adjustment but shall remain stationary during any tests, the measuring being done by the movement of the knife edge which shall be effected by micrometer screws working in slides parallel to the optical axis and transversely in any position angle. The whole apparatus to be fixed on a solid stand also possessing all necessary adjustments.

11. Adequate arrangements for maintaining the temperature of the testing room constant and for the easy and safe handling, adjusting and collimating of the mirrors during testing shall be provided. Provision for the Hartmann test shall be made if required.

12. All the mirrors including the auxiliary plane shall fulfil the above requirements and shall be tested by the representative of the Government and any other person or persons who may be asked to act. The maker shall provide all necessary facilities for these tests.

13. Five ordinary and one wide field eyepieces of suitable foci for visual observations at both the Newtonian and the Cassegrainian focus shall be provided, with the necessary adapters for holding, as well as the necessary guiding eyepieces for the double slide plate holder.

14. Two finders of four inches aperture shall be attached in convenient positions at the lower end of the tube. One long focus finder of seven inches aperture and of focal length about that of the main tube shall be attached to the latter and shall be provided with eyepiece with illuminated cross wires. Lateral adjustment of the eyepiece by means of rectangular slides allowing movement of about 15 minutes of arc in any direction, with means of clamping when adjusted, shall be provided.

MOUNTING

1. The general form of mounting is that having a long polar axis supported on separate columns with the declination axis passing through the polar axis between the bearings. The tube is mounted on one end of this declination axis as close to the polar axis as possible, balance being restored by a system of counterweights on the far end of the declination bush. Reflectors mounted in a somewhat similar manner are the 4-foot Melbourne, the 4-foot Paris and the 37½-inch Ann Arbor.

2. A spectrograph which may extend as much as eight feet below the mirror cell is to be attached to the lower end of the tube. With the type of mounting described no difficulties are introduced when the tube is on the meridian or above the polar axis. But as it is frequently convenient to work with the tube under the axis, the length of the polar axis, the form of the columns and other conditions shall be so arranged as to allow this method of working so far as is possible without making the instrument out of proportion or affecting the stability and cost of the mounting. If it is not possible under these conditions to swing eight feet then the design shall be arranged to allow as long an extension as possible. The diameter of the upper end of the spectrograph will not exceed three feet, while the lower end will be only about half that size.

3. The north and south piers shall be of cast iron provided with means of adjustment in altitude and azimuth and shall carry the bearings of the polar axis in spherically shaped seats to allow of this adjustment without introducing constraint on axis or bearings. Only so much of these piers as may be considered necessary to provide ample means of adjustment and to allow of proper driving and working of the instrument need be of iron construction and part of the telescope.

4. The polar axis shall be constructed in the best manner of the materials most suitable for the purposes it has to fulfil. If of built-up construction especial care must be taken to ensure its remaining in alignment when finished. All the bearing surfaces on this axis, as those for the main bearings, for the driving worm wheel, for the main driving gear, for the R.A. circle or any others must be truly concentric with one another and should if possible be finished by grinding at one swinging in the lathe. The greatest care must be taken in boring the bearings or bush for the declination axis to ensure that it is exactly at right angles to the polar axis. If this condition is not fulfilled it is impossible to properly adjust the telescope.

5. The declination axis shall be forged in one piece of steel of the best quality for the work it has to do and all bearing parts as well as those carrying gears or other attachments shall be turned and ground perfectly concentric with one another.

6. The diameters and sections of the polar and declination axes shall be of sufficient size to carry the required weights without undue flexure. The amount of flexure allowable shall be decided by the Government representative.

7. The bearings on both polar and declination axes shall consist of roller bearings entirely. The practice of depending on plain cylindrical bearings for the alignment and of relieving some of the friction by counterpoised rollers, mercury flotation, or other methods is to be abandoned and both alignment and friction taken care of by roller bearings only. Whether bearings like the Timken Roller Bearing (which provides means of adjustment to take up wear and lost motion) or straight cylindrical roller bearings

are to be used will be decided later. In either case the rollers must be prevented from getting out of place and from sliding against one another by some form of cage or by intermediate smaller rollers. It is essential that the rollers and the external and internal bearing sleeves shall be of steel, hardened and ground with the greatest of accuracy.

8. The end thrusts shall also be cared for by means of anti-friction bearings, preferably of the roller type and also without sliding friction. Means of adjustment on one of the end thrust bearings on the declination axis will be necessary.

9. Timken roller bearings or some equally good friction relieving device shall be applied to other bearings in the telescope where friction will be liable to affect the easy and smooth movement of the telescope. Some that may be mentioned are—the bearing of the worm wheel on the polar axis, of the slow motion arm on the declination axis, of the shafts transmitting quick motion in R.A. and Dec. and any others deemed desirable.

10. The principle to be followed in designing the quick and slow motions and the setting circles is to have the maximum of convenience in operation with the minimum of complication and expense. To this end the following general scheme is suggested though any modifications proposed will be considered.

11. Quick motion in R.A. shall be effected by means of a hand wheel on the south pier, gearing as directly as possible into a large fixed gear on the polar axis. The setting circle in R.A. shall be so arranged that it may be conveniently read from the quick motion wheel and this circle shall be driven at the sidereal rate so that one may set directly to the R.A. of the star without calculation for hour angle. No fine graduations are required but the ruling and figures shall be sufficiently distinct to be read directly without magnifier or telescope to minutes of time, and allow of estimation to fifths of a minute. An hour circle coarsely graduated to five minutes of time will also be required.

12. Taking into account accessibility and simplicity the best method of obtaining the quick motion in declination seems to be by an electric motor mounted on the declination bush and gearing into a large gear keyed to the outer end of the declination axis. This motor shall be actuated from a switch near the R.A. hand wheel, while the declination circle might be near the large gear and read directly from the switch. A moderately coarse graduation easily read without telescope and yet admitting of estimation to 5 minutes of arc and if feasible by some auxiliary device even closer is required.

13. The clamp in right ascension should be near the hand wheel and a clutch for disconnecting the latter from the axis if considered necessary. The clamp in declination must be near the quick motion switch and it is necessary to arrange an interlocking device so that the act of clamping will disconnect the motor and that the tube must be unclamped before it is possible to start the motor.

14. The foregoing specifications have shown that the intention is to have the preliminary quick setting and clamping of the telescope in R.A. and Dec. made from one position at or near the south pier as probably the most direct and convenient place.

15. The slow motions in both R.A. and Dec. shall be effected by means of electric motors, these motors being actuated from small switch contacts which may be held in the hand of the observer and of which there shall be two sets, one at the upper and one at the lower end of the tube to enable the final setting and guiding to be done at the finders and guiding eyepieces.

16. The slow motion in R.A. shall be applied by means of differential gears in the worm shaft or clock train, these gears being driven by a small motor and no arm and tangent screw motion is necessary.

17. The slow motion in declination shall also be actuated by means of an electric motor, the necessary communicating mechanism being sufficiently rigid to ensure that the tube may be started and moved in declination smoothly and without springiness or lost motion. Friction in the mechanism must be relieved by rollers or balls so that when unclamped the tube may move easily and freely.

18. The speed for the quick motions shall be about 45° to the minute and for the slow motions about 30 minutes of arc to the minute, and the motors must be provided with some kind of brake or clutch so that the telescope stops when the switch is opened.

19. The tube above its attachment to the declination axis shall be of skeleton construction, below of closed construction. The lower part shall be of cast iron, or steel and cast iron, or of other materials as may best answer the purpose. Such openings in the sides of the lower section near the mirror, closed by light removable covers, as may be deemed necessary for convenience in burnishing the mirror or for other purposes shall be made.

20. The mirror cell shall be of cast iron of substantial construction, rigidly attached and yet easily removable for the purpose of resilvering. The mirror shall be supported on the back in the cell by a system of counterweighted levers or by any other suitable system, such as a multiple three-point support, which will equally distribute the weight of the mirror. An edge support system like that used on the 60-inch Mount Wilson telescope shall be used to maintain collimation without undue stress on the edge of the mirror.

21. As the latest experience has shown that nothing is gained so far as temperature effects on the mirror are concerned by leaving the cell open at the back it may preferably be entirely closed in, except a central aperture as large as the hole on the mirror.

22. An attaching ring about 3 feet in diameter shall be cast on and turned up true on the bottom of the cell with convenient appliances for attaching and orienting the spectrograph and other accessories.

23. Some convenient and effective means of covering the mirror which shall at the same time act to a certain extent as a heat insulator shall be provided.

24. For the skeleton section of the tube above the declination axis, the construction shall be as light as is consistent with maintaining the mirrors in good collimation. As a first approximation the amount of flexure allowable at the Cassegrain mirror situated about 19 feet above the surface of a 60-inch and nearly 23 feet above a 72-inch mirror shall not exceed one-eighth of an inch when the tube is horizontal. The flexure when the instrument is used in the prime focus with the heavier extensions required need not be so small and a tube to carry the Cassegrain with the above flexure would be sufficiently rigid for all purposes.

25. The upper end of the tube shall be so designed as to allow the necessary changes from one form of the telescope to another (Cassegrain, Newtonian and prime focus) to be made with the minimum of risk, labour, and change of balance.

26. The Cassegrain mirror which for a 72-inch telescope is of about 19 inches aperture and situated nearly 23 feet from the surface of the principal mirror must be held firmly and yet without constraint in its cell and cell and mirror shall be capable of being easily and accurately adjusted for collimation. After collimation has been effected the system must be movable with a slow smooth motion along the optical axis for the purpose of focussing. This motion must be carried by rods and gearing to the lower end of the tube near the guiding eyepiece of the spectrograph and must not change the collimation. The mirror and system are to be held in position by four arms of thin steel plate, placed edgewise, attached firmly to the periphery of the tube.

27. When the telescope is used in the Newtonian form or at the prime focus the Cassegrain must be removed to prevent obstruction of the light and when used at the prime focus the Newtonian mirror must be removed for the same reason. One double slide plate holder attachable either at the Newtonian or prime focus with the necessary focussing and adjusting devices and guiding eyepieces shall be provided. When used at the prime focus provision must be made for carrying the plate holder movements and guiding eyepiece to the side of the tube. The plate used in this plate holder will be 4 inches square and care must be taken in the design that light from the whole mirror except that occulted at the centre shall reach every part of this plate unobstructed. The Newtonian attachment and also that in the prime focus shall be provided with convenient means of rotation and clamping in position angle to bring the plate holder or other attachments to a convenient position for guiding. The adapters or attachments in which the plate holder is held must be designed to admit of the use of a small spectrograph.

28. The tube must be attached to the declination axis at such a place that with the Cassegrain in place and no spectrograph below the mirror the tube is nearly in balance. Balance will be restored when the spectrograph is attached by weights placed north and south of the upper end of the tube. Provision for attaching weights below the cell for restoring balance when the other attachments are in use must be made.

29. The driving clock shall be of ample size to do the work and made in the best manner. Great care must be taken with the communicating gears and shafts between the governor and the worm shaft to prevent the introduction of any periodic error in driving. The clock shall be wound automatically by an electric motor.

30. The connection between clock and worm shaft shall be as direct as possible and, if differential gears are introduced in the worm shaft, care must be taken that the two parts of the shaft are exactly concentric else a period may be introduced. Provision must be made in the connection to allow the adjustment of the telescope in altitude and azimuth without affecting the driving.

31. The driving worm itself which is often at fault must be most carefully made. It must be turned and the worm cut as truly as possible and finished by grinding. The screw part should be left considerably longer than will be used and ground and lapped in a long nut to remove all chance of periodic error.

32. The driving worm wheel shall be as large as possible in diameter. If the design of the polar axis is properly carried out, the worm wheel might, when the telescope is turned to the pole, the only place where interference can occur, project up behind the mirror cell for at least a foot as the spectrograph or any other attachment below the cell

will not be greater than 3 feet in diameter. The worm wheel is to be spaced and cut with the greatest possible accuracy. The teeth shall be smoothed up and any remaining irregularities removed by running worm and wheel together with polishing material, care being taken that all grinding material is removed from worm and wheel. The whole driving mechanism must be carefully made as periodic error in driving is a most annoying and troublesome defect.

33. A complete and permanent system of wiring for illuminating the circles and guiding eyepieces and for the quick and slow motion motors with 12 additional wires for the spectrograph shall be provided on the telescope but bearing rings and brushes to be avoided if possible.

34. For transport conditions it is desirable and almost essential that no single piece of the telescope weigh more than five tons.

35. The price given shall include the cost of boxing and delivering f.o.b. at the place of manufacture and the services of a competent person to superintend the erection of the instrument, which shall not be considered completed until it operates to the satisfaction of the representative of the Government.

36. Terms of payment desired should be stated in the tender.

TENDERS

Preliminary enquiries had been sent early in March to a number of firms who were deemed competent to construct the optical parts and mounting of a large telescope and after the specifications were prepared, they were sent to the following firms with the privilege of tendering for either the optical or mechanical parts or for the complete telescope :—

Sir Howard Grubb, Dublin, Ireland.
 The Jno. A. Brashear Co., Pittsburgh, Pa.
 The Warner & Swasey Co., Cleveland, Ohio.
 The Alvan Clark Son's Corporation, Cambridge, Mass.
 T. Cooke & Sons, York, England.
 O. L. Petitdidier, Chicago, Ill.
 G. W. Ritchey, Pasadena, Cal.
 Carl Zeiss, Jena, Germany.

In the meantime, I had sailed for Europe and first visited the Grubb works at Dublin. Sir Howard Grubb did everything in his power to assist me in regard to the design of the telescope, and showed me the various telescopes under construction in his works. He explained his proposed design for our reflecting telescope and we thoroughly discussed all details. I found that our ideas in regard to the essential features were in substantial agreement, although I did not like his design so well as the preliminary design of the Warner & Swasey Co.

He advised me to consult Sir David Gill and suggested that if he, Sir Howard, got the contract, Sir David would probably be willing to supervise the construction, as he was already doing in the case of telescopes for other distant clients, and kindly made an appointment for me with the latter in London. Sir David I found a most charming

person, very interested in the project and he offered several valuable suggestions, but nothing radically different from what was already incorporated in the design. Similarly the Astronomer Royal was eager to be of any possible service and I have the same story to relate of all whom I consulted. There is no question but that all these opinions were of service and I certainly obtained the widest possible viewpoint and the benefit of the most varied experience in these discussions of the design of the telescope.

While in Paris, through the kindness of Comte de la Baume Pluvinel, I had the pleasure of a conference with M. Delloyé, the manager of the St. Gobain Glass Co., the firm who would be entrusted with the casting of the mirror disc, and I was very pleased to learn from him that they did not expect any serious difficulty in making a 6-foot disc with a hole in the centre. I suggested to him a method of forcing a core through the glass after pouring, in preference to pouring around a core in place. Prof. G. W. Ritchey had been especially insistent on the impossibility of obtaining a good disc with a hole cast in it, stating that when the molten glass flowed around the central core the continuity of the flow was broken and the metal did not perfectly unite on the opposite side. However, M. Delloyé did not inform me how they expected to accomplish the task, but I imagine from the appearance of the hole in the disc as received that it was produced by a core being forced through after pouring. The final result showed that Prof. Ritchey's misgivings were not borne out and there was absolutely no evidence of lack of homogeneity in the disc in any place.

On my return from Europe I found that actual tenders for construction had been received from the following firms :—

For the construction of the mounting :—

Sir Howard Grubb of Dublin, Ireland.
The Warner & Swasey Co. of Cleveland, Ohio.

For the construction of the optical parts :—

Sir Howard Grubb of Dublin, Ireland.
The Jno. A. Brashear Co. of Pittsburgh, Pa.
The Alvan Clarks Sons' Corp. of Cambridge, Mass.

Tenders were given for both 60-inch and 72-inch apertures, the latter being about 30 per cent higher in price. In view of the comparatively small difference in price it was decided to recommend the construction of a 72-inch telescope.

The tenders of the Warner & Swasey Co. of \$60,000 for the mounting and of the Jno. A. Brashear Co. of \$30,750 for the optical parts were considerably lower than the others, the only serious competitor being Sir Howard Grubb. Owing to the fact that the Warner & Swasey Co. had considerably more experience in the construction of large telescopes, and were much better equipped than Sir Howard Grubb for work of this character, and to the further important fact that they were situated in a place readily accessible from Ottawa, where the design and workmanship could be efficiently supervised, it was a matter for congratulation that their tender and that of the Brashear Co's. for the optical parts, to whom the same considerations apply, were the lowest. No difficulty in regard to price was in the way of awarding the contracts to the firms, whom it was considered were in a position to produce the best instrument.

The next stage naturally was the placing of the orders for the telescope and as the preliminary authorization from the minister had only been for making enquiries and obtaining prices, it was necessary to obtain the authority of the Governor General in Council for the awarding of the contracts. Under instructions from the minister, Dr. King prepared a memorandum setting forth the reasons for the construction of the instrument, the proposals and prices received and recommending the awarding of contracts to the Warner & Swasey Co. and the Jno. A. Brashear Co. for the construction of a 72-inch reflecting telescope.

The minister's recommendation based on this memorandum was assented to by the Government on October 18, 1913, and the construction of the telescope hence assured. It is easy to imagine the relief and delight of those interested in the undertaking when it was learned that the matter was finally settled, and that the project initiated three years earlier, and carried out only by constant and untiring efforts during the interval, had been finally brought to a successful issue, and Canada was to have a telescope more in keeping with her character and aspirations and one with which the work so successfully inaugurated with the 15-inch telescope could be enormously extended.

I wish to express here my sincere appreciation of the help so readily and cheerfully given by so many scientific associations and individuals in bringing the matter to the attention of the Government, and of the co-operation and active help of members of the Cabinet and members of Parliament in interesting the minister and through him in finally having the construction authorized by the Government. Finally I desire to particularly express to the Hon. Dr. Roche, the Minister of the Interior during the development, construction and organization stages of the undertaking, my deep gratitude for his hearty support and cordial co-operation, in the carrying on of the work during a difficult time, and for his just and sympathetic treatment in the final organization. I venture to hope that not one of the smallest of Dr. Roche's claims to the recognition of posterity will be his progressive and public-spirited attitude in regard to the cause of astronomical research in Canada. I am also very much indebted for the success of the undertaking and for the arranging of the organization to the hearty co-operation of Mr. W. W. Cory, Deputy Minister of the Interior.

CHAPTER III—DESIGN, CONSTRUCTION AND LOCATION.

Immediately upon the passing of the order in council authorizing the construction, the successful tenderers were notified. Contracts were then prepared governing the relations of the two parties, the character of the work, the method of inspection and approval and the terms of payment, which were finally signed.

In the matter of the optical parts, preliminary details were fairly well settled by the specifications and moreover, when the optical constants of the instrument had once been settled on, there are no alternative means of accomplishing the desired objects as is the case in the mounting. For example when the specifications say the mirror must be of 72 inches aperture, of 360 inches focal length, and must be a paraboloid of revolution within certain close limits, no modifications are possible and there was no room for change of detail or method as in the case of the mounting.

The glass discs for the principal mirror, 73 inches diameter, 12 inches thick, the auxiliary plane 55 inches diameter, 9 inches thick and for the Newtonian and Cassegrain secondaries were ordered by the J. A. Brashear Co. from the St. Gobain Glass Co. in November 1913. After one unsuccessful trial the principal mirror was successfully cast and annealed in July 1914. Although the disc for the auxiliary plane was not ready, fortunately the 73-inch disc and the small mirror discs were shipped to the Brashear Co. late in July 1914 from Antwerp, only three or four days before war was declared. They arrived in Pittsburgh about the middle of August and work was at once begun on the rough grinding and shaping. This was completed and the fine grinding and polishing of both back and front finished in August 1915. Various delays then occurred and actual figuring was not commenced for a year and not completed until April 1918. More complete details will however be given in the description of the telescope.

In the case of the mounting the specifications were purposely and necessarily not so specific as for the optical parts, as it was deemed very desirable to allow the makers, especially with their valuable experience in the construction of large refracting telescopes, every scope to exercise originality in design and to improve upon existing methods in the details of the mounting and in the means employed to accomplish the desired operations.

A preliminary design had already been prepared by the Warner & Swasey Co., which embodied fairly closely the main features of the specifications and this design was elaborated and modified as soon as their tender was accepted.

I was deputed by Dr. King to collaborate with them in the design of the instrument and it was agreed by all that it would be very desirable to give a great deal of attention to this part of the work. Various consultations were necessary and as these could not be effectively carried on by correspondence, it was decided that I should go to the works of the Warner & Swasey Co. whenever necessary for the proper working out of the design, to decide between alternative proposals and to approve details when satisfactory.

Consequently, very soon after construction was authorized I visited Cleveland and spent three or four days most profitably and pleasantly in discussing and deciding upon the main features of the mounting. A young engineer of the company, Mr. Walter Fecker, was entrusted with the preparation of the detail drawings under the supervision of the works manager, Mr. E. P. Burrell, who is responsible in great measure for the working out of the design, while the general features of the mounting and its harmonious appearance are due largely to the genius of Mr. Swasey.

The plan adopted at these conferences, of which several took place before the completion of the drawings, was to go over the work already done, discuss and note all features in which modifications seemed desirable and plan the means to be employed for accomplishing the desired ends. These conferences undoubtedly were of great value in perfecting the design and in serving to efficiently combine the astronomical and mechanical requirements of the telescope. On the one hand the great experience and knowledge of Mr. Swasey as exemplified in the design of the largest and most successful refractors ever built, and the ingenuity and engineering skill of Mr. Burrell and his engineering staff ensured an instrument mechanically and structurally correct, while on the other hand, my own mechanical knowledge and training enabled me to more correctly gauge and adapt astronomical requirements to mechanical execution. The result was,

I firmly believe, a telescope very considerably in advance in design, construction, and perfection of workmanship and operation of any hitherto made.

I would not be doing justice to the Warner & Swasey Co. if I did not warmly express my appreciation of the spirit in which they undertook and carried through this work. Once the contract was awarded, their one aim was to make the telescope the best possible, regardless of cost or of whether the specifications called for the inclusion of any particular feature. Not once in all our conferences did they offer objection to any improvement or addition suggested by me and often they themselves, even at considerable additional cost, incorporated features in the design which would increase the efficiency, accuracy or convenience of the instrument.

Our relations throughout the design, construction and erection of the telescope were of the most cordial nature and I carry the pleasantest memories not only of the interesting and friendly character of our business relations but of the kindly and hospitable way in which I was looked after and entertained by the members of the firm during my numerous visits to Cleveland. These and the equally cordial and pleasant relations with the Jno. A. Brashear Co. in the construction of the mirror, made the superintendence of the construction of this telescope an especially agreeable and interesting task.

The various features of the design and the variations from general practice will be dealt with particularly in the description of the mounting and it has seemed best in this place to give merely a summary of the stages in the progress of the work. Even before the contract was entered into, in October 1913, considerable progress had been made in the preliminary design, which was elaborated, detailed and modified as soon as construction was decided on. The greater part of the design and most of the detail drawings were completed by the summer of 1914, although some small changes were made in minor details after construction had been commenced. The Warner & Swasey Co. have not the facilities for machining and handling the heaviest parts of such a mounting and consequently the large steel castings for the polar axis, the central section of the tube and the mirror cell were sublet to the Bethlehem Steel Co. A local concern made and machined the largest of the iron castings such as the south bearing for the polar axis and the large worm wheel and spur gears. All the other work and the assembling and fitting were done at the works of the Warner & Swasey Co.

The larger parts of the mounting hence were ordered and the construction of the small parts begun at Cleveland in the fall of 1914. Most of the heavy parts were completed and on hand in Cleveland in the early summer of 1915 and the fitting and temporary erection of the mounting begun at Cleveland. There was insufficient head room for the erection in the main factory so this was carried out in an annex especially adapted for this purpose and proceeded without hitch or serious delay.

The work on the mounting was completed and the fitting and preliminary erection finished early in 1916. Before the telescope was dismantled preparatory to shipment to Victoria, the Warner & Swasey Co. were desirous of having a reception and private view of the mounting for astronomers and others interested in it. Owing to the ill health and absence of Mr. Swasey, and to the illness and subsequent death of Dr. King, this was postponed until May 25, 1916. Invitations were sent to leading astronomers

and men of science in America and although not many astronomers were able to be present, a pleasant and successful reception was held and the mounting was duly shown and appreciated.

Immediately after this function the mounting was taken down, some further detail work whose need had arisen in the erecting was completed and it was then packed and shipped in four cars via car ferry Ashtabula to Port Burwell and thence C.P.R. to Victoria. Shipped about the end of July 1916, it arrived in Victoria about the middle of August. Final erection commenced on Sept. 6 and was completed about Oct. 15.

LOCATION OF TELESCOPE

Before proceeding to the description of the optical parts and mounting, it is desirable to give an account of the steps that led to the location of the telescope near Victoria and of the stages of construction there.

During the early stages of the project and until the memorial of the Royal Society of Canada was brought forward in 1912, there had been no thought on the part of either Dr. King or myself, of locating the telescope elsewhere than at Ottawa. This idea was first broached by Prof. J. C. McLennan who was good enough to bring forward and heartily support the resolution before the Royal Society. He urged that a clause should be incorporated in the memorial making provision for placing the telescope at the most suitable location, for astronomical purposes, in the Dominion. I am frank to confess that neither Dr. King or myself were at first in favour of this clause as we felt that the difficulty of getting the project authorized by the Government would be much increased if location away from the observatory at Ottawa, which would necessarily mean considerably increased cost of construction and maintenance, were considered. We were well aware of the difficulties in the way of inducing the Government to consent to the large appropriation for purposes of purely scientific research without complicating the matter by further requiring the establishment of a separate institution, a new observatory at some point in Canada away from the seat of Government.

However, I am glad to say that Prof. McLennan insisted on this clause being inserted and the memorial went through in this form and was finally assented to as related above. After Dr. Roche had authorized the making of enquiries, in regard to the design and cost of the telescope, consideration was given to the question of location. The first step was to carefully compare the meteorological records for various regions of Canada, selected on the advice of Sir Frederic Stupart, the director of the Meteorological Service, as being representative of different climatic conditions in the Dominion. Ottawa was considered as being fairly representative of conditions in the eastern part of the country as although some other localities might have a greater quantity of clear sky, there was little likelihood of the important factors of "seeing" and diurnal range of temperature being much more favourable at any location east of the great plains. From the meteorological records, Medicine Hat was selected as being probably the most favourable situation on the prairies, Banff in the Rockies, Penticton at the foot of Okanagan Lake for the dry belt in British Columbia, and finally Victoria, a region of low precipitation and remarkably small diurnal range of temperature, for a situation influenced by the presence of surrounding sea water.

These places were visited by me on my journey to obtain information in regard to the design of the telescope and arrangements were made to have the sky around the pole photographed every night in order to determine the relative clearness of the night skies at the various places. Although from the meteorological records it was possible to determine the relative merits of these locations so far as clearness of sky in the day-time, range of temperature, wind velocity and humidity were concerned, these records furnished no information in regard to what experience has shown is the most important factor, the "seeing", the relative steadiness of the atmosphere which governs the crispness of definition of the star image. The quality of the "seeing" can only be judged by actual observations with a telescope, the larger the better, for it is quite possible that "seeing" apparently good with a small aperture may go to pieces under the much severer test imposed by a telescope such as the 72-inch.

Consequently, Mr. W. E. Harper, the senior officer in the Department of Astrophysics in the Observatory at Ottawa, was deputed to observe the conditions at the locations mentioned above with a 4½-inch Cooke Photo-Visual telescope, the largest portable instrument available. Observations were made at Ottawa first and a plan devised which enabled the relative value of the "seeing" at the various stations to be accurately compared. Mr. Harper spent most of the summer of 1913 in this work and a full account is given by him in the Publications of the Dominion Observatory, Ottawa, Vol. 2, p. 275.

This account may be briefly summarized by saying that so far as the conditions of "seeing" and small daily range of temperature are concerned, Victoria was much superior to any other place tested. The "seeing" was on the average 3.5 on a scale of 5 as compared with 2.5 at Penticton and about 2.0 at Ottawa. In daily range of temperature Victoria had only slightly more than half the range present at either Penticton or Ottawa. So far as Banff and Medicine Hat were concerned, the "seeing" was hopelessly poor and these places were not further considered. Again as there was little difference between Ottawa and Penticton the latter was eliminated from the discussion which was hence narrowed to Ottawa and Victoria. Meteorological records of the number of hours of bright sunshine at the two places showed an advantage in favour of Ottawa of about 10 per cent. This difference, however, is negligible in view of the superiority of Victoria in the "seeing" and temperature conditions and recent experience has shown there is probably also a greater number of hours of clear night sky at Victoria than at Ottawa.

To obtain some definite numerical conception of what these differences entailed in the amount and quality of the work possible at the two places, the matter was referred to Prof. Campbell, director of the Lick Observatory and Prof. Adams of the Mt. Wilson Observatory both of whom have had experience in work with reflecting telescopes. When their replies were analysed and combined they indicated, so far as could be definitely judged, that the superior conditions of "seeing" and the low daily temperature range would enable more than double the quantity of work of higher quality and accuracy to be performed at Victoria and would further render possible of production certain kinds of work at Victoria which the poor "seeing" conditions at Ottawa would prevent.

There seemed, therefore, to be no room for doubt that the telescope should be placed at Victoria and from this time, October 1913, I was a strong advocate of Victoria as the

only place for the telescope. Dr. King, however, was not so enthusiastic, as he probably realized more clearly than I did the financial and administrative difficulties involved. As the tests had been made only during the summer months he thought it desirable to also compare Victoria and Ottawa during the winter. Consequently, Mr. Harper was sent to Victoria in November 1913 and remained there until Christmas. Although the weather was cloudy and broken the relative advantage of Victoria over Ottawa in both "seeing" and temperature was increased and there hence remained no reasonable doubt that the telescope should be placed at Victoria. Although I am convinced that if he had consulted his personal feelings, Dr. King would have much preferred this splendid instrument to have been placed at Ottawa, as part of the great scientific institution he had built up, where it would have been under his direct supervision and control, yet he placed the scientific work to be done as the first consideration and prepared a strong recommendation in favour of locating the telescope at Victoria.

As the capital cost of installation away from Ottawa would be much greater, an office building and residences for the astronomers being required in addition to the observatory building and dome, which only would be needed at Ottawa, it was considered desirable to see if the Government of the Province of British Columbia would assist the project in some way. The erection of such a large telescope near Victoria would be a great educational and advertising asset and if some aid could be obtained from the Province, the Dominion Government would be much more likely to sanction its location away from Ottawa. Consequently, I visited Victoria in February and March 1914 on such a diplomatic mission and interviewed the Premier, Sir Richard McBride, and several members of the Government to see if they could help the project and thus make its location at Victoria more probable. In this mission I had most effective aid from Mr. Arthur W. McCurdy of Victoria, a gentleman interested in scientific pursuits who had considerable influence with the Premier. As the upshot of the matter, the Government of British Columbia offered to give \$10,000 towards the purchase of the site and to build a road to the summit of the hill on which the observatory was to be located.

Provisional selection was also made at this time of the most suitable site in the neighbourhood of Victoria. It was felt that the conditions which gave Victoria its good "seeing" might be quite localized in extent as less than ten miles away the rainfall was doubled. Consequently, some situation near to and easily accessible from Victoria on an isolated hill to obtain the advantages of air drainage and more uniform temperature was sought. On the Saanich peninsula are five elevations of this character, Mt. Wark, 1,400 feet, Mt. Newton, 1,000 feet, Mt. Douglas, 728 feet, Bear Hill, 725 feet, Saanich Hill, 730 feet. Both Mt. Wark and Mt. Newton are much more difficult of access than the others and though higher, it is doubtful if the conditions would be superior as the former is in a mountainous district and is not an isolated hill, while Mt. Newton has very gradual approaches and would have no advantages over lower hills rising more directly from the general level. Of the other three, Saanich Hill is in every respect the most suitable. It is situated about 7 miles north of Victoria, the electric interurban railway passes the foot of the hill making it much more easy of access than the other two, and there is a considerably greater area around the summit suitable for the buildings required. Hence,

pending the final decision of the Government as to location of the observatory, the summit of this hill was provisionally selected as the site.

As soon as the definite offer of the Provincial Government was received, I returned to Ottawa, and Dr. King prepared a complete memorandum to council on the question of location, strongly recommending the placing of the observatory at Victoria. This was finally approved and the matter definitely settled in April 1914, thus enabling the design of the mounting, which depends on the latitude of the observatory, to be completed. Further, as soon as it was settled and before the public announcement, steps were taken to obtain the land required for the observatory grounds. Consequently, I returned to Victoria and attempted to obtain options at a reasonable figure. Real estate even over the rocky inaccessible summit of this hill was held at fancy prices and it was only after protracted negotiations that the 50 acres needed were obtained at \$280 per acre.

After the land had been obtained and surveyed, the question of a water supply and of the road had to be arranged. Three alternative surveys of a road from the West Saanich road to the summit were made by Mr. Devereaux, a very capable Provincial surveyor, but it was only after a struggle with the Provincial Department of Public Works that the only one which would serve our purpose and give access to the proposed buildings was agreed on. The road was built in the spring of 1915, is of a uniform and gradual grade of about 7 per cent., is splendidly constructed and a credit to the surveyor and the Department. The water question was also a difficult one as there was no supply within reasonable distance. A well drilled on the lowest part of the property proved a failure in the dry season, while a second well on adjacent property gave only about $1\frac{1}{2}$ gals. per minute, an inadequate supply. Finally, a running spring of about 4 gallons per minute on the right of way of the B.C. Electric Railway, which the management generously allowed the observatory to use, was piped into a reservoir and from thence pumped up by electric power to the summit under a head of 500 feet, into a large tank of 30,000 gallons capacity. This spring gives water of excellent quality, though somewhat hard, and will probably be sufficient for the immediate future.

CHAPTER IV CONSTRUCTION OF OBSERVATORY BUILDING AND ERECTION OF TELESCOPE.

Contemporaneously with these problems the question of the design and construction of the building and dome for the telescope were also pressing questions, and required a great deal of urging and diplomacy to get them under way in time to be ready for the telescope. The building and the concrete pier for the telescope were designed by the Department of Public Works and contracts for their construction were let in the early summer of 1915. The dome, which, in the case of a large reflecting telescope, really acts as a working accessory, had necessarily to be designed by the Warner & Swasey Co., who spent a great deal of time and ingenuity in making it most complete and convenient in every particular. The contract for its construction and erection was let to the Warner & Swasey Co. by the Department of Public Works in the fall of 1915, and was at once got in hand.

The massive concrete pier for carrying the telescope was commenced in June 1915 and required two visits by the writer, the first for giving a meridian line for orienting properly and the second for setting the templates and foundation bolts for the north and south pier heads of the polar axis. The latter task was a difficult one as little range for adjustment was allowed and the bolts had to be most accurately placed, the upper set at an angle of $48^{\circ} 31'$ to the lower. The pier was finished in September and the surrounding circular steel building which serves as substructure for the dome, erected during the fall and winter of 1915-16.

The dome was constructed very rapidly, temporarily erected in Cleveland in March 1916, and shipped to Victoria arriving there in April. Erection proceeded promptly and the structural members were in place and the operating mechanism partly installed by the end of June. The installation and adjustment of the operating mechanism was completed during the erection of the telescope mounting in October. The double sheet metal covering was started in July but proved a tedious process, also not completed until October, about the time of the completion of the erection of the telescope mounting. Fortunately no rain fell during this period and everything proceeded smoothly and without trouble or delay.

As previously related, the telescope mounting which had been entirely erected and fitted in Cleveland, was taken down during June and July 1916 and packed on 4 cars for shipment to Victoria. Wherever possible, the auxiliary mechanism was left attached in place and such pieces as the driving clock, which is an independent unit in a separate case, was shipped intact and consequently much adjusting and fitting at Victoria avoided. The heaviest single pieces were the polar axis, $9\frac{1}{2}$ tons, the central section of the tube 7 tons and the south pier head 7 tons.

According to the provisions of the contract the Warner & Swasey Co. were to provide a competent man to superintend the erection of the telescope, and their superintendent, Mr. Decker, an able and experienced engineer, was chosen for this work. In order that his services might not be lost to the Company for a longer period than necessary, I had agreed to do all the preliminary preparatory work possible before he was sent for.

I arrived in Victoria early in July and found the erection of the structural work and most of the mechanism of the dome completed but none of the operating accessories had yet been tested as the motor generator set was not installed. The first thing to be done was to arrange for the hoisting tackle and for the methods of handling the heavy and at the same time delicate mechanism with the greatest ease and safety. The most difficult part of the erection would be the hoisting of the polar axis and setting it in place in its bearings. For the axis alone weighed $9\frac{1}{2}$ tons and before putting in place, the driving worm wheel, the main driving gear, the hour and sidereal circles, the clamping mechanism in right ascension, and the radial and thrust bearings had to be placed on the axis and adjusted in position. The total weight to be hoisted then was about 14 tons and as it had to be lifted at the proper angle and let down into position with the greatest nicety and care, it was evident that hoisting tackle of ample strength and yet capable of being controlled with accuracy and ease was required.

I was fortunate in securing for this work a firm of contractors, Messrs. Skillings and Hamon, who had experience in handling heavy work and who undertook to haul the parts

of the mounting from Victoria to the building, to provide the necessary tackle and experienced help for handling the work. As the main ribs of the dome were sufficiently stiff to carry any of the weights to be hoisted, the problem was thereby simplified and there only remained the question of the tackle. I was unwilling to trust any of the rope tackle obtainable in Victoria and it was decided to use wire cable. Mr. Skillings was able to rent a house moving outfit consisting of a horse driven capstan, about 700 feet of $\frac{7}{8}$ -inch wire cable, the part to be used being in good condition, and a set of heavy cable blocks with the necessary snatch blocks, etc. The capstan which had been so long exposed to the weather as to be rather shaky was practically rebuilt and was fastened to the roadway north east of the building, being securely anchored by cables to adjoining trees. The cable from this capstan passed horizontally over the ground floor of the building and was led up by a snatch block to the set of blocks attached to the main ribs of the dome. By means of a horse attached to the walking beam of the capstan any piece attached to the lower block was raised slowly and gradually about one foot per minute, a pawl and ratchet on the capstan cylinder acting as a safety catch and allowing the piece to remain in one position as long as desired. This device proved very safe and convenient and the difficulties of the erection were thereby lessened.

The mounting which was shipped from Cleveland the last week in July via car ferry Ashtabula to Port Burwell, thence C.P.R. direct to Vancouver and thence by car ferry again to Victoria, arrived about the middle of August and Skillings and Hamon at once started the hauling to the observatory. This required nearly two weeks but as soon as some of the heavy parts were on hand the hoisting from the ground floor to the observatory floor began. The first pieces to be handled were the north and south pillow blocks or pier heads, the latter weighing 7 tons and the former about 5 tons. These were lifted directly up from one of the main ribs and set in position over their foundation bolts. The south pier head was levelled by steel wedges and the relative position of the two measured. It was found that the two bearings were closer together than they should have been, although still within the range of adjustment provided. This was probably due not to error in setting, but to settlement of the inclined forms of the north pier owing to the great weight of concrete, or to shrinkage or settlement in the setting of the mixture.

I determined that before the polar axis was installed these two bearings should be adjusted as closely as possible so that the final adjustment of the axis, which if of any magnitude, would require readjustment of clock and driving worm, would only be small. Consequently, a steel wire was stretched between the centres of the north and south bearings and the north adjustable bearing was moved until this wire was as nearly as possible parallel to the axis of the earth. This parallelism was determined first in azimuth by setting up a 6-inch micrometer transit theodolite over a fixed reference point about 50 feet south of the building from which the whole of the wire was visible and from which the bearing of certain objects in Victoria 7 miles away had previously been determined in orienting the pier. It was hence comparatively simple to adjust the north bearings so that the wire lay in the meridian. The transit was then placed in the building close to the south pier, on the same meridian line as the wire, and the bearings adjusted in altitude until the wire made an angle of $48^{\circ} 31'$, the latitude of the observatory, with the horizontal.



Fig. 1. Parts of Telescope on Observing Floor.

This preliminary adjustment saved considerable trouble in the final adjustment, by following, of the polar axis as the north end was found to be out of position in a length of 20 feet about 0.03 inch in azimuth and 0.02 inch in altitude and no secondary adjustment of clock and driving worm was necessary for these very small angular deviations, less than one-half and one-third of a minute respectively.

The balance of the mounting with the exception of the central section of the tube, the worm wheel, and the declination axis were hoisted to the observing floor and left in convenient positions for the final erection. A general idea of the arrangement can be seen in Fig. 1.

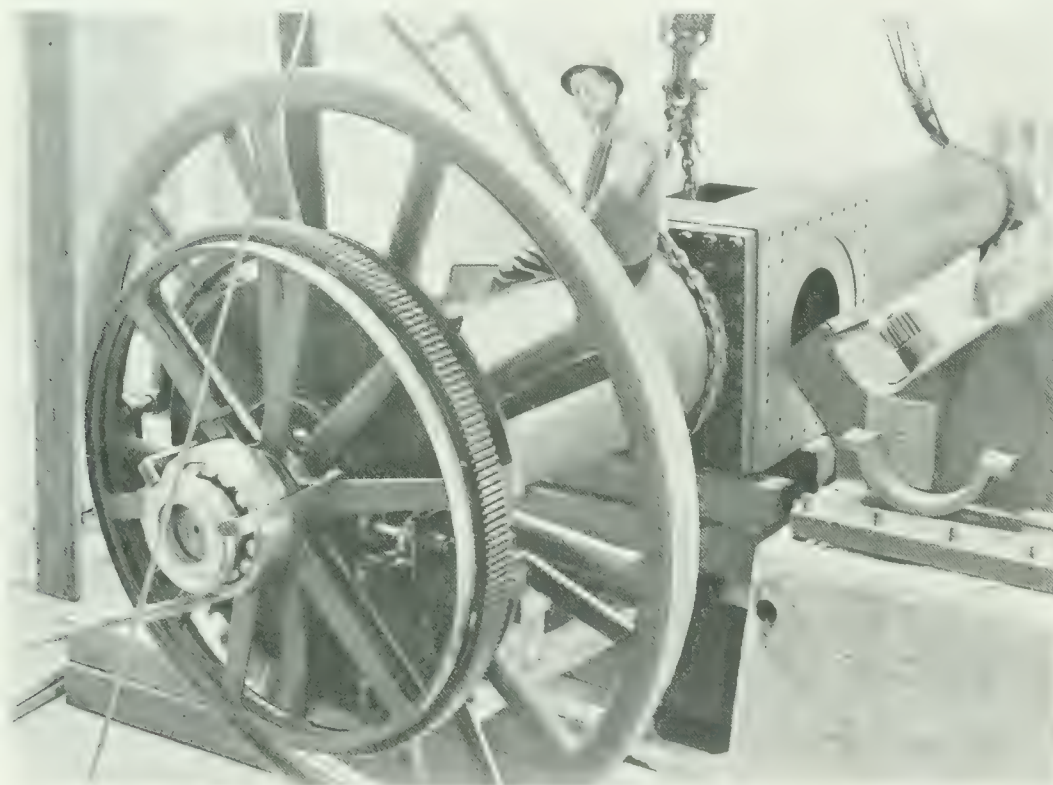


Fig. 2. Polar Axis ready for hoisting.

This preliminary work was completed about Sept. 1 and as soon as Mr. Decker arrived, on Sept. 5, erection was commenced. The polar axis itself had been hoisted to the observing floor from one of the main ribs and the first step was to place in position on it the worm wheel, main driving gear, circles and bearings. As in setting in position the axis had to be central the hoist was taken from both ribs connected by a long double link and the axis was hence raised directly over its position of rest. The axis was so attached to the lower block that when it was raised from the floor the north end was at approximately the right elevation and when elevated above the bearings only small changes in position had to be effected in order to let it down into place. As previously stated, the weight was about 14 tons and it was necessary that no strain should be put on any of the wheels or circles. Hence as it had to be lowered in one particular way and into a close fitting

position, it was an anxious time until finally in place. A photograph of the axis ready to be hoisted is given in Fig. 2.

After the polar axis was in place, about three days after erection commenced, the other large parts in the order, declination sleeve, declination housing, declination axis, centre section of tube, skeleton tube and mirror cell were soon erected and all the large parts of the mounting were attached ten days after erection started. The attachment and adjustment of the clock and smaller parts, especially the electrical work, took considerably longer and it was not until Oct. 15 that the wiring was completed and all the switchboards, motors, solenoids, condensers, etc., correctly connected.

In the meantime, and while waiting for the completion of the electrical work, the operating accessories of the dome had to be fitted and adjusted, the cables for dome, shutter, curtains and platform attached, the canvas wind screens put in place, the trolleys and trolley wires for carrying current to the shutter curtain and platform motors erected, the silvering car and declination strut put together and in place, and numerous other details attended to.

However, the whole work was completed in about six weeks without hitch or accident of any kind, a remarkably short time considering the magnitude of the undertaking, giving convincing evidence of the care used in the design, construction, and preliminary fitting and erecting of the installation.

Adapters had been made for attaching the long focus finder objective and ocular centrally along the axis of the tube, and the adjustment of the polar axis was tested and improved by Schlesinger's method of following a star through the meridian. The adjustment was made nearly correct at this time but was not finally completed until the following summer to allow for further settlement of the piers. As previously stated, only a very slight change was found necessary in the position of the axis, which did not require readjustment of clock and worm.

I returned to Ottawa early in November as there was no prospect of the mirror being finished until the following spring, Mr. T. T. Hutchison, who had been appointed Engineer, being left in care of the mounting. In the spring of 1917, the observatory was formally organized as a branch of the Department of the Interior, the writer being appointed Director of the institution, which was named the Dominion Astrophysical Observatory, while Dr. R. K. Young was given the title of Assistant Astronomer. Preparations were then made for permanently moving to Victoria and as it was still uncertain how soon the mirror would be finished, it was decided to go to the observatory in July, as there was a very considerable amount of necessary preparatory work which could profitably be done before the mirror arrived.

As related elsewhere, the completion of the mirror was delayed until April 1918, but the spectrograph arrived about the first of January and its installation and adjustment the preparation of dispersion tables, preliminary work on the observing programme, and other details were attended to so that no time should be lost in commencing work when the mirror was completed. As detailed in the description of the optical parts the mirror was completed early in April 1918 and was packed and shipped to Victoria.

The 72-inch mirror was left in the strong cast iron cell in which it had been ground and polished and a strong wooden cover was bolted on the open top of this cell, thereby

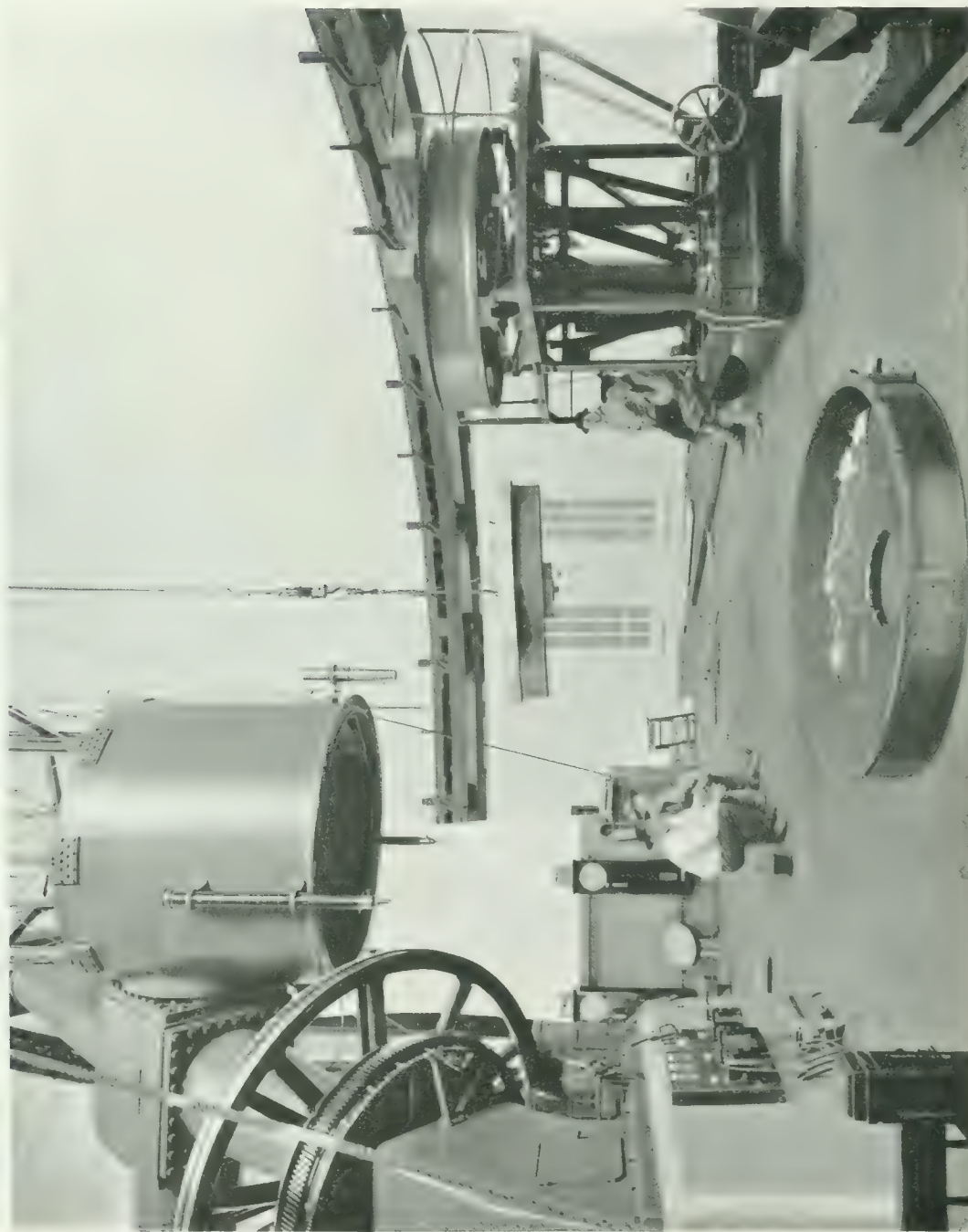


Fig. 3. Raising the Mirror.

completely enclosing the mirror. This was then packed in a large wooden box with excelsior,* and it and the other optical parts were shipped by express in a through car to Victoria, so that no trans-shipment at any point was necessary. It went through without delay, arriving in Victoria on April 28, six days after leaving Pittsburgh, and was hauled out to the observatory the second day following without accident or hitch of any kind.

A very satisfactory and safe way of handling the mirror, placing it in its cell and installing on the telescope had been devised. No risk of accident could be taken and consequently great care in the selection of the hoisting apparatus, and in the hitches and fastenings required was exercised. The wooden box in which the mirror was shipped was about 7 feet 6 inches square and 2 feet deep, and in order to get inside the entrance door, was turned up on edge and run in on rollers. The opening in the observing floor through which it had to be lifted, was about 7 feet 6 inches by 3 feet 6 inches and would not allow the outer box to pass through. The Brashear Co. had provided a strong eyebolt screwing into one of the trunnions of the iron cell, and consequently the mirror, encased in its iron cell with wooden cover, was lifted the 21 feet to the observing floor on edge and gently let down, face up, on blocking.

In the meantime the mirror cell of the telescope had been removed from the tube and the wooden box filled with boiler punchings of the same weight as the mirror, which had been used to balance the telescope similarly to its final condition, was removed by means of the silvering car which is elsewhere described.

A good view of the silvering car and of the methods used in handling the mirror is given by the three photographs showing the installation of the mirror. The vertical truss supporting the outer end of the declination axis can be seen in Fig. 5, and when not used is pushed down in its guides below the floor and a cap placed in the opening.

The silvering car was used in the installation of the mirror, as the figures indicate. The mirror was lifted vertically upward between the tube and the silvering car, by tackle attached by an eyebolt to a padded wooden block below the central hole Fig. 3. The silvering car was then rolled on its track directly under the mirror, which was let down on the timbers shown in Fig. 4. Three shorter pieces of 6 by 6 timber were cut, placed vertically on the frame of the silvering car, passing up between the ribs of the cell. The plunger was then run downwards until the mirror was supported on these three timbers. The tackle and horizontal timbers were removed and the cell raised by the plunger slowly and steadily into position about the mirror. The only risk involved in this process was the chance of accident with the tackle, and a very large factor of safety had been provided. After the mirror was placed in its cell, in proper position with regard to its counter-weighted bottom and edge supports, it was only a matter of half an hour to attach it to the tube and, although every precaution against accident had been taken, every one concerned felt very much relieved when the mirror was finally in place and the telescope at last completed.

It was only a week after the mirror reached Victoria until it was installed, collimated, and the first star spectrum obtained, which is, I think, a record-breaking performance for such a large telescope. Even though the mounting had been erected and adjusted, still all the tackle had to be placed and attached, the Cassegrain silvered and collimated



Fig. 1 Mirror resting on Cell on Silvering Car.

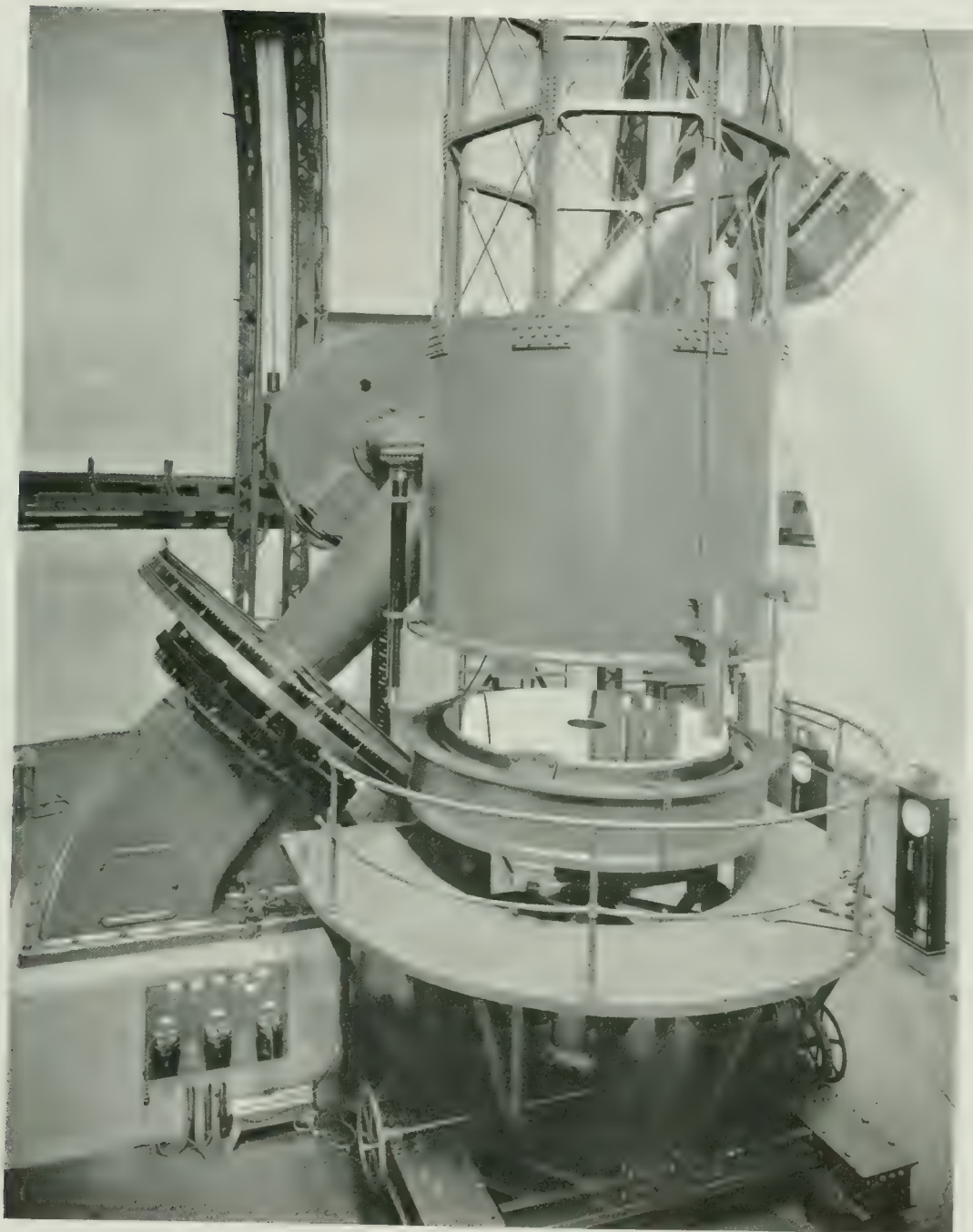


Fig. 5. Mirror and Cell ready to attach to Tube.

and the telescope rebalanced. I think it speaks volumes for the care used in the design and construction of the mounting and accessories, that there was no delay or hitch from any cause and that the telescope operated perfectly from the first without any alteration or further adjustment being required.

CHAPTER V—DESCRIPTION OF THE OPTICAL PARTS

The telescope was planned to be used in the Cassegrain or Newtonian form or directly at the principal focus to do away with the additional reflection. For the same reason, the presence of a central hole in the main mirror was deemed essential, as otherwise three reflections would be required with the Cassegrain form besides forcing the spectrograph into an awkward, unsymmetrical and inconvenient position at the side instead of being as now in a prolongation of the axis of the tube.

As previously mentioned strong objections were brought forward by Prof. Ritchey to the idea of having a central hole cast in the mirror on account of the probably non-homogeneous character of the resulting disc. But the great advantages of the direct passage for the beam from the Cassegrain made an opening through the centre of the main mirror so desirable that I decided to take chances on having a hole cast in the disc, as being less dangerous than attempting to bore one later, especially as the manager of the St. Gobain Co. did not seem to anticipate trouble. As matters turned out, the disc is a beautiful piece of glass with not a sign of a bubble or lack of homogeneity anywhere near the central hole.

The disc when received by the Brashear Co. in August 1914 was about $73\frac{1}{2}$ inches in diameter, from 13 to $13\frac{1}{2}$ inches thick and with a central cored hole tapered, irregular and slightly eccentric about 6 inches in diameter at one side of the disc and 8 inches at the other. The weight was very nearly 5,000 lbs. The appearance of the hole seemed to indicate that the core had been forced through after pouring rather than that the glass had been poured with the core in place. Even the first inspection before grinding showed the glass to be an exceedingly fine specimen when its size is considered, and this good opinion was enhanced when the surfaces were polished and the interior could be readily examined. Only at one place in the mass, a place near the edge and extending tangentially about six inches and radially two or three, are a few small bubbles. Elsewhere the material is remarkably free from bubbles or other defects and appears perfectly homogeneous and uniform. It is of course unnecessary to say that the few bubbles present will be absolutely without effect on the performance of the mirror.

Although the disc was apparently well annealed, the greatest care was used in the rough grinding process, especially around the central hole, to take off the outer skin slowly, and to avoid any temperature effects in the grinding. Over 600 lbs. of glass were removed in the grinding, the finished mirror weighing 4,340 lbs., being 12 inches thick at the edge, 73 inches in diameter, while the central hole was increased in size to $10\frac{1}{8}$ inches in diameter to enable direct photographs to be made in the Cassegrain focus if desired.

In the preparation of the specifications questions had arisen as to the best thickness to make the mirror and many authorities favoured having it as thin as possible, consistent with maintaining its form during the figuring processes and when in use. The idea was that it would more rapidly assume the observing temperature and would not be so much deformed under changing temperature. My own idea was that, as it would hardly be safe to attempt to figure a mirror of this size if less than 8 inches thick, it might as well be 12 inches thick so far as accommodating the interior to changing temperature was concerned, while the greater stiffness as well as the greater distance between back and front would tend to diminish any deformations due to changing temperature. Consequently as the opticians preferred it to be as thick as possible to avoid danger of change of form during figuring and testing, the disc was left 12 inches thick.

After the disc had been rough ground all over, the back was fined and polished approximately flat and the front surface was fine ground to the correct radius, 720 inches, and polished.

The surface was polished and ready for the figuring in August 1915, about a year after the disc was received, but the actual figuring did not begin until about a year later. This was due to the fact that the material for the auxiliary testing plane which was to be 55 inches in diameter was not available. Various attempts were made to have such a disc cast in America and one was poured in 1916 at the works of the Pittsburgh Plate Glass Co. However, it devitrified in annealing and as the mounting was now being erected at Victoria, it seemed unwise to wait longer in the hope of getting a disc made.

Prof. Geo. E. Hale, director of the Mt. Wilson Solar Observatory, had kindly offered to loan the Brashear Co. the 60-inch plane used by Ritchey in parabolizing the 100-inch mirror. Unfortunately at the time it was needed at Pittsburgh, it was being used at Pasadena in parabolizing the 100-inch and would be required some months longer for the testing of the Cassegrain secondaries.

Hence it was decided after consultation with the Brashear Co. to go on with the parabolizing, depending upon measurements of the radius of curvature of different zones of the surface to obtain the required amount of parabolization and using a plane 33 inches in diameter which the Brashear Co. already had, and which had been proved very accurate, for detecting any slight zonal irregularities in the surface. Indeed as the hole in the main mirror was 10 inches in diameter, it is evident that this plane would more than cover a section along a radius and that theoretically at least it could be used for testing the whole surface. Practically, however, it was found that difficulties arose in attempting to use it wholly in the testing and some misleading results were obtained by its use. Consequently it was found necessary to depend chiefly on the tests at the centre of curvature, the difference of radius for different zones being computed and compared with the measured values, while the plane was chiefly used in testing the smoothness of the curvature and in detecting minor zonal irregularities.

This is quite in line with the experience of Prof. Ritchey in figuring the 100-inch mirror for, according to the 1916 report of the Solar Observatory, it was found that even with a 60-inch plane, considerably larger in proportion than the 33-inch with the 72-inch, the principal reliance was placed on tests at the centre of curvature.

A very convenient method of making these radius tests was devised by Dr. Brashear and merits description here. The whole surface of the mirror was covered by a paper diaphragm along the horizontal diameter of which a number of concentric slots were cut about an inch wide and six inches long. These slots were spaced every four inches along the diameter, thus enabling the radius of curvature of 8 zones of the mirror to be measured. These zones were spaced 35, 31, 27, 23, 19, 15, 11, 7 inches on each side of the centre and enabled the character of the correction obtained to be accurately determined. Each of these zonal slots was covered by a cardboard valve and these valves could be lifted by strings carried back to the centre of curvature enabling any particular zone to be uncovered by the measurer as desired. This was a great advantage over having all the zones uncovered as it removed all confusing effects and difficulties of identification and enhanced the ease and accuracy of determining the radius of any particular zone.

The artificial star was fixed in position near the centre of curvature, and instead of making micrometer measurement by the Foucault method of the position of the knife edge, it was fixed on an accurate and easy moving slide to which a short straight edge at right angles to the movement was attached. A piece of paper or card was pinned under this straight edge and when the position of equal darkening for any particular zone was determined, a line was ruled on the paper by a sharp pencil against the straight edge. When all the zones were measured there would be 8 transverse lines on the card whose positions could be compared at a glance with the positions of similar lines ruled on a card at the theoretically required distances. This method enabled the condition of the surface to be determined at a glance, was more direct, simple and rapid than micrometer measures and of practically equal accuracy.

Experience showed that these charts could be repeated with only very slight deviation and that the probable error of determination of radius of a zone would not exceed 0.01 inches equivalent to 0.0025 inches at principal focus. Naturally the radius of the outer zones, where the convergency of the pencils was greater, could be determined much more accurately than those nearer the centre.

The parabolization of the surface was begun about September 1916, was halted for two or three months by the cold weather of the winter and resumed in March 1917. The Brashear Co. expected to complete the surface in the spring or early summer of 1917 but unexpected difficulties arose, most of which were due to the presence of the central hole. This large opening, $10\frac{1}{8}$ inches in diameter, necessitated the cutting away of a similar portion in the centre of the full-sized parabolizing tool and this caused an irregular and unexpected shape of the surface near the central opening. The only remedy was local polishing by smaller tools, and the surface was nearly finished in August 1917, when through some unexplained cause it became scratched. Although these scratches would not have affected the performance of the mirror, Mr. McDowell would not consent to allowing them to remain and the only recourse was to polish them out by a full size tool and refigure.

By October the surface was again nearly finished but unfortunately in smoothing up some minor irregularities produced in the local work, the centre was deepened too much, and although about 90 per cent of the usable surface was practically perfect, and the remainder not far out so that the mirror would have done excellent work, the

Brashear Co. were still unwilling to let it go and another fresh start was made. Although the cold weather was now coming on and the firm were very crowded by important war work the figuring of the mirror was persistently continued and profiting by past experience was finally completed on April 3, 1918.

I was summoned by telegram on March 20 to come to Pittsburgh and test the mirror as the Brashear Co. were undecided whether to continue the correction a little further or to allow it to remain as on that date. On arriving there on March 28, I found the outside zones practically perfect while there was a slight undercorrection in the inner 40 inches diameter. This undercorrection was equivalent to a longitudinal aberration at the focus of about half a millimetre, this part of the surface being of longer focus than the remainder. Although this is very small and would probably have no discernible effect on the definition, it was decided to see if the effect of changing temperature would tend to increase or diminish the error. A series of measurements of the radii of the various zones showed that all changes of temperature possible inside the testing tube appeared to increase the deviations from true figure and although the mirror would probably behave quite differently when silvered and under observing conditions it was considered that it would be preferable to reduce the undercorrection and to have the surface as nearly correct as possible under constant temperature.

Consequently local polishing on the required part of the surface was carried on for four times and on April 3, the mirror was considered finished as the measurements showed no deviation between the measured and computed positions greater than one millimetre, equivalent to a quarter millimetre at the principal focus.

The 72-inch mirror was then accepted and after silvering, was tested by the Hartmann method of extra focal images in the constant temperature testing tube at the

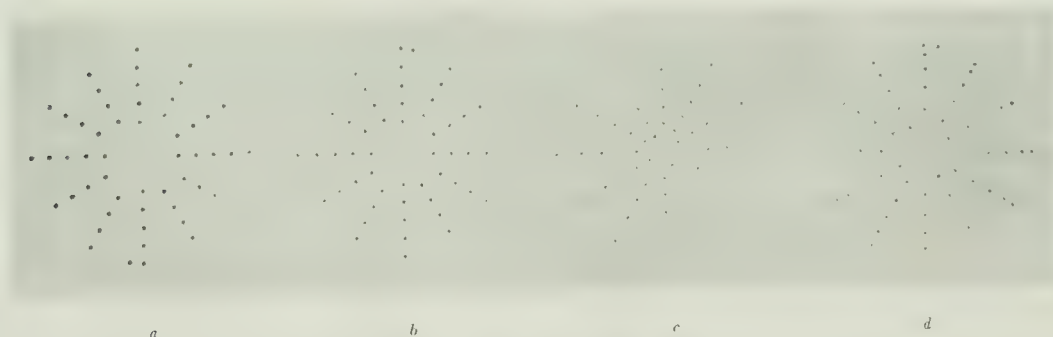


Fig. 6. Images from Zone Plate.

Brashear factory. For this purpose a diaphragm of stiff manilla paper was stretched on a light wooden frame of such size as to cover the whole surface, and 60 circular holes about $1\frac{1}{2}$ inches in diameter were cut in this diaphragm. These holes were spaced along 6 diameters of the mirror 30 degrees apart, 10 holes in each diameter and were so arranged that on each of 15 zones of the mirror, spaced 2 inches apart between a radius of 7 inches and a radius of 35 inches, were 4 holes on two diameters 90 degrees apart. Hence two measurements of the radius of each of the 15 zones at points on the mirror 90 degrees

apart could be obtained and complete information in regard to astigmatism as well as zonal aberration could be secured. The extra focal images, *a* and *b*, Fig. 6, taken at the principal focus give a good representation of the spacing of the diaphragm.

As a parallel pencil of 72 inches diameter could only be obtained in the testing tube by the aid of a 72-inch plane which was not available, it was necessary to make this test at the centre of curvature. Consequently an artificial star formed by an acetylene flame and a small pinhole was set up slightly to one side of the centre of curvature of the inner zones and a plate holder carrying plates 2 by 3 inches and held in a sliding frame was placed on the other side in a position to intercept the reflected pencil from the mirror. With the star fixed at twice the focal length from the centre, the intersections or foci of the pencils from the various zones do not all come to one point as in the case of a sphere but are spaced, with a paraboloid of revolution, at various points along the axis given

by the formula $\rho = 2F + \frac{R^2}{2F} + \frac{R^4}{16F^3}$ where

ρ = Radius of curvature of zone of diameter $2R$.

F = Focal length of mirror.

R = Radius of any zone of surface

or the intersections will be at distances of $\frac{R^2}{2F} + \frac{R^4}{16F^3}$ beyond the star.

These distances have been computed for the actually measured radii of the zones uncovered by the Hartmann diaphragm and are given in Table I. It is evident that at points a short distance inside and outside the position of the star the reflected pencils will form on a screen or plate an image or pattern somewhat similar to the diaphragm over the mirror but that owing to the spacings of the intersections over a distance of about 1.6 inches these will be differently distributed in the two positions of the plate, crowded together at the centre for the plate inside the focus and towards the outside for the plate beyond the focus. A reproduction of two of these plates are given at *c* and *d* Fig. 6 where *c* is the plate taken inside, *d* that outside the focus. Owing to this unsymmetrical arrangement and to prevent confusion of the images, it was necessary to separate the two positions of the plates to a much greater distance than would have been necessary if the test could have been made at the focus with parallel light. Observations with an ocular showed that the most advantageous positions were about 5 inches inside and 7 inches outside the focus. Several exposures were made at these two positions on both Seed 23 and Process plates. As there was no chromatic aberration, which in the case of this test with a lens tends to elongate the images, the resulting images were round, uniform and easy to accurately bisect in a micrometer microscope.

After the mirror was silvered it stood about 28 hours when the first series of plates were made in the evening hours. But as it was felt that perhaps the temperature conditions might not have been normal, owing to disturbances caused by setting up the apparatus, adjusting collimation, etc., a second series was made early the following morning after the tube had been undisturbed for over 10 hours. Six of these later plates were measured, three on each side of the focus, and the reliability of the determination was shown by the very close agreement of the measure of the different sets. As the plates

were all made at the same distance inside and outside focus, the means of the three sets of measures were taken and the position of the intersection of the pencils from the different zones determined from these mean values. The principle of the method is very simple as is shown by the accompanying diagram. Fig. 7.

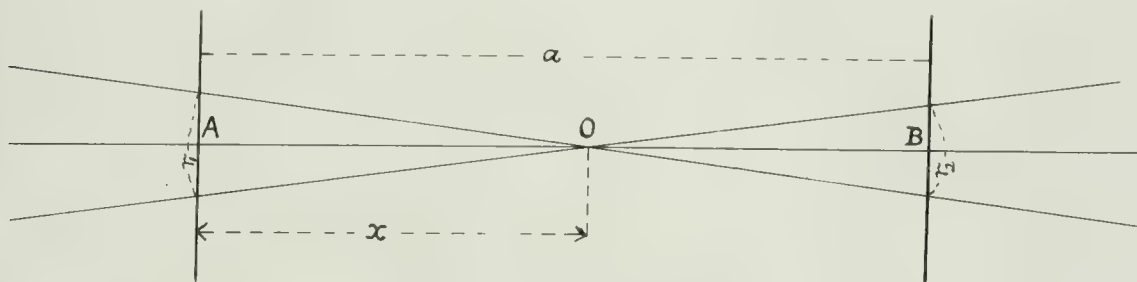


Fig. 7. Principle of Hartmann Method.

If the two pencils intersect in O, the distance between the plates A and B is a , and the distance apart of corresponding zonal images on A and B is r_1 and r_2 then from similar

triangles the distance OA or x is obtained from $\frac{r_2}{a-x} = \frac{r_1}{x}$ or $x = \frac{ar_1}{r_1 + r_2}$.

The results of the measures are given in Table I.

TABLE I—ZONAL ABERRATIONS OF 72-INCH MIRROR

Separation of Apertures in Zone Plate.		Computed Focal Distances.		Measured Focal Distances.		Residuals O. C.		Mean Zonal Difference.	Aberration at Focus.
1st Quad.	2nd Quad.	1st Quad.	2nd Quad.	1st Quad.	2nd Quad.	1st Quad.	2nd Quad.	Inches.	Milli-metres.
70·10	70·12	1·702	1·703	1·689	1·680	—·013	—·023	—·018	—0·11
66·14	66·16	1·515	1·516	1·539	1·499	+·024	—·017	+·003	+·02
62·04	62·16	1·332	1·338	1·394	1·262	+·062	—·076	—·007	—·04
58·12	57·98	1·169	1·164	1·152	1·129	—·017	—·035	—·026	—·16
54·00	54·10	1·011	1·015	1·026	·983	+·015	—·032	—·008	—·05
50·13	50·00	·870	·865	·884	·821	+·014	—·044	—·015	—·09
46·12	46·01	·736	·732	·743	·730	+·007	—·002	+·002	+·01
42·09	41·98	·613	·610	·644	·596	+·031	—·014	+·008	+·05
38·00	38·00	·499	·499	·563	·513	+·064	—·014	+·039	+·24
34·12	34·12	·403	·403	·463	·405	+·060	+·002	+·031	+·19
29·96	30·06	·310	·312	·328	·295	+·016	—·017	·000	·00
25·94	26·24	·232	·238	·272	·215	+·040	—·023	+·008	+·05
22·06	22·00	·166	·167	·211	·145	+·045	—·022	+·011	+·07
18·12	17·96	·114	·111	·126	—·050				
13·93	14·12	·067	·069	—·024	—·054				

NOTE.—In this table the first two columns are the measured distances between the separate pairs of apertures in the zone plate, the angles between any two pairs in the 1st and 2nd quadrants being 90°. The third and fourth columns are the computed distances of the knife edge from the star, the latter being at the centre of the osculating sphere. The fifth and sixth columns contain the measured distances of the intersections of the pencils from the corresponding apertures, the zero point of the scale corresponding to the weighted mean position of best focus. The seventh and eighth columns contain the residuals between the computed and observed positions of the intersections for the various zones. The ninth column contains the mean zonal difference in inches and the tenth the deviation or aberration at the principal focus in millimetres.

As previously stated for every zone two measures are made in directions 90° apart. As the mirror was in a closed tube only two or three inches wider and higher than the mirror it is likely there would be some stratification of the air in horizontal layers and that the bottom of the tube would be the coolest and the top the warmest. Unfortunately no thermometers to determine the temperatures were available but the measures themselves show an indication of this effect. The diaphragm was so placed on the mirror that the one set of zonal openings were all situated in or within 30 degrees of the vertical plane and the other set in or within 30 degrees of the horizontal plane. The measures show that the residuals around the vertical plane are generally positive and those around the horizontal plane negative. The mean difference in focal length for the two planes is about a quarter of a millimetre, the focal length in the vertical plane being the longer and although such difference, if real, would have little effect on its performance, I am convinced that it is wholly a temperature effect. Indeed the zonal plates themselves show evidence of this as will be noticed in the reproductions in Fig. 6 where the asymmetry at the bottom is markedly shown. The effect is probably due partly to unequal differential refraction of the pencils in passing through the stratified layers and partly due to temporary astigmatic form produced in the mirror by the horizontal temperature gradients from bottom to top. The enormous quantity of polishing with a full-sized tool which was required to remove scratches inadvertently obtained at two stages of the figuring would ensure almost absolute certainty of the figure being a perfect surface of revolution.

That such is the case is seen below from the tests of the mirror in the telescope where, at any rate for the plates of May 19 where the temperature was practically stationary, there is little likelihood of unequal temperatures at different orientations and though there appear to be accidental and irregular small variations due possibly to errors of measurement, there is no indication whatever of any systematic differences or of any astigmatism in the mirror.

Consequently the mean value for the two sets was taken and the differences in inches at the centre of curvature for the different zones was reduced to residuals in millimetres at the principal focus.

It will be noticed that the residuals in the last column, (those from zones of 7 and 9 inches radius which are entirely covered by the shadow of the Newtonian and Cassegrain mirrors being not determined) representing longitudinal aberrations at the principal focus, are remarkably small, the maximum 0.24 mm. for a zone 19 inches radius, and the mean less than 0.1 mm. These figures show that the surface is remarkably close to the theoretical form, with apparently little greater deviation than about an eighth of a wave length from the true paraboloid. This accuracy is much within the unavoidable aberrations produced by changing temperatures on the form of the surface and by unsteadiness of the seeing on the definition of the image and the mirror may be considered practically perfect.

These tests were made in the testing tube at the Brashear factory, where the daily change of temperature is very small, and it was not expected that the mirror could show the same perfection of figure under actual observing conditions. It was consequently a matter of great interest and importance to determine the figure of the mirror after it had been installed in the telescope when it was exposed to the changing temperature conditions in the dome, rising during the day and falling at night.

The mirror was finished on April 3 and at once silvered and as soon as the Hartmann test was completed the figuring of the Cassegrain secondary was begun. In order to test this surface during figuring a parallel pencil was needed and to provide this only the 33-inch plane was available. Consequently only a section of the Cassegrain along a radius could be seen in the test, less than half the diameter, and the difficulty of figuring and testing was much increased. Nevertheless the skill of Mr. McDowell soon overcame these difficulties and the figuring of the secondary only occupied about a week. This figure could not be tested by the Hartmann method in the optical shop but was tested later in the telescope with the result to be given below.

Immediately on completion, arrangements for packing and shipping were made and the principal and auxiliary mirrors left Pittsburgh on April 23 in a special express car, came through direct to Victoria without transshipment, arriving in six days, on April 29th. The mirror was soon installed on the telescope, a description of the method being given in another place, and the first test spectrum obtained on May 6.

Hartmann tests of the figure of the 72-inch mirror under actual observing conditions were made on May 12th and 19th. The same zone plate as used at Pittsburgh was placed over the surface of the mirror, the double slide plate holder placed on the focussing ring at the centre of the tube, which has a total movement of about 6 inches, hence enabling extra-focal photographs to be readily obtained. Exposures of 5 to 10 secs. on Vega or 30 seconds on a second magnitude star suffices to give good extra-focal zonal photographs on fine-grained plates and a set can be obtained in a few minutes. The distance inside and outside focus in this case when the photographs are practically replicas on a reduced scale of the zone plate is not very material but from an inch to an inch and a half both inside and out seemed to give the best defined and best measurable images, two of them being reproduced in Fig. 6, *a* inside, *b* outside focus. The measures of the plates in this case of course gave at once the residual zonal aberrations at the principal focus of the mirror without reductions as was necessary when the test was made at the centre of curvature.

The results obtained are particularly interesting and instructive as the test on May 12 was made under conditions representative of the average good night's temperature range while on May 19 the temperature variation was abnormally small, thus giving the figure of the mirror under average observing conditions, and again under nearly the ideal case of constant temperature.

The temperatures on the two days are given for short intervals in Table II and the times of tests are also indicated so that the temperature conditions surrounding the mirror can be seen at a glance.

TABLE II—TEMPERATURE CONDITIONS AT TESTS

May 12			May 19			May 19—con.		
Time	Temp.	Exposures	Time	Temp.	Exposures	Time	Temp.	Exposures
	F.			F.			F.	
6 A.M.	52°		Mt.	56° 6		10 30 P.M.	53° 6	
8 "	54.8		2 A.M.	56.0		11.00 "	53.5	Exposure 4
10 "	56.8		4 "	55.7		11.30 "	53.0	
12 "	58.2		6 "	55.7		12.00 Mt.	52.4	
2 P.M.	59.3		8 "	56.0		12.30	52.4	" 5
4 "	61.0		10 "	56.1		13.00	52.2	
6 "	62.0		12 "	56.1		14.00	52.1	" 6
7 "	62.0		2 P.M.	56.0		15.00	52.1	
8 "	61.0		4 "	56.0		16.00	52.3	
8.15 "	60.8	Dome opened	6 "	56.1		17.00	53.0	
9.10 "	56.9	Exposure 1	8 "	56.0	Dome opened	18.00	54.2	
9.30 "	56.3		8.20 "	54.4	Exposure 1	20.00	56.8	
10 "	55.8		8.30 "	54.0	" 2			
10.30 "	55.2		9.00 "	54.0				
11 "	55.1		9.30 "	54.0				
11.30 "	54.9	Exposure 2	10.00 "	53.9	" 3			

Table III gives the zonal foci for the two tests on May 12 and as in Table I the positions of focus are given for two positions at right angles to one another for each zone. This is done in order to show whether there is any sensible astigmatism in the surface.

TABLE III—ZONAL TESTS MAY 12

Radius of Zone	Exposure 1			Exposure 2			Differences of Focus	
	Focus Quad. 1	Focus Quad. 2	Mean Focus	Focus Quad. 1	Focus Quad. 2	Mean Focus	Exp. 1	Exp. 2
in.	mm.	mm.	mm.	mm.	mm.	mm.	mm.	mm.
35	45.75	45.81	45.78	43.23	43.44	43.33	0.00	0.00
33	46.26	45.74	46.00	44.03	43.50	43.76	.22	.43
31	46.08	46.34	46.21	43.87	43.96	43.81	.43	.48
29	46.81	46.42	46.61	44.06	43.83	43.94	.83	.61
27	46.84	46.75	46.80	44.51	44.18	44.34	1.02	1.01
25	46.87	47.52	47.20	44.51	44.77	44.64	1.42	1.31
23	47.68	47.11	47.40	45.11	44.84	44.97	1.62	1.64
21	48.05	47.03	47.54	44.98	44.98	44.98	1.76	1.65
19	47.41	48.04	47.72	45.02	45.35	45.18	1.94	1.85
17	48.02	47.48	47.75	45.56	45.00	45.28	1.97	1.95
15	47.92	48.07	47.99	45.09	45.27	45.18	2.21	1.85
13	47.94	48.83	48.23	44.52	46.05	45.28	2.45	1.95
11	49.79	48.92	49.35	46.55	45.21	45.88	3.57	2.55

TABLE IV—ZONAL TESTS MAY 19

Radius of Zone	Foci at Exposure 2			Mean Foci at Exposures			Differences of Focus at Exposures			
	Quad 1	Quad. 2	Mean	3	5	6	2	3	5	6
in.	mm.	mm.								
35	44.11	43.89	4.00	3.65	3.09	2.93	0.00	0.00	0.00	0.00
33	44.50	44.74	4.62	4.08	3.52	3.51	.62	.43	.43	.58
31	44.52	44.45	4.48	4.07	3.54	3.33	.48	.42	.45	.40
29	44.30	44.41	4.36	3.82	3.31	3.07	.36	.17	.22	.14
27	44.61	44.57	4.59	4.04	3.30	3.00	.59	.39	.21	.07
25	44.74	44.54	4.64	3.90	3.35	3.05	.64	.25	.26	.12
23	44.67	44.73	4.70	4.17	3.60	3.33	.70	.52	.51	.40
21	44.99	44.64	4.81	4.25	3.34	3.26	.81	.60	.25	.33
19	44.97	44.82	4.89	4.25	3.51	3.25	.89	.60	.42	.32
17	44.80	44.54	4.67	4.07	3.48	3.13	.67	.42	.39	.20
15	44.98	44.47	4.67	4.00	3.44	2.91	.67	.35	.35	— .02
13	45.03	44.29	4.66	3.91	3.36	2.96	.66	.26	.27	+ .03
11	44.69	44.66	4.67	3.80	3.15	2.13	.67	.15	.06	— .80

Table IV gives the zonal foci for four tests on May 19 when the temperature was nearly constant but in only one of these are the positions given for the two quadrants as the other three are practically similar.

An examination of Tables III and IV in comparison with Table I is illuminating as showing the effect of changing temperature on the figure of the mirror. On May 12 the dome temperature had gradually risen from 52° F. at 6 A.M. to a maximum of 62° at 6 to 7 P.M. and, when the dome was opened at 8.15, the temperature had fallen to 60°.8. When the first exposure was made about an hour later, it is hardly probable the decreasing temperature had been acting sufficiently long to change the figure appreciably and the resultant under-corrected figure, over 3 mm. longer focus at centre than edge, is due probably to the increase in temperature in the dome during the day. At the second exposure made 2 hours and 20 minutes later, the decreasing temperature has begun to show, and the positive aberration, under-correction, is slightly reduced.

On May 19th when the temperature had been practically constant throughout the day and had only dropped about 2° in the half hour between the opening of the dome and exposure 2, the first measured, the figure is very nearly normal and were it not for the outer zone of 35 inches radius, would be practically perfect. The same is true for all the exposures although the focal length of the centre is continually shortening relatively to the edge under decreasing temperature. The action of falling temperature on the mirror evidently is to introduce negative aberration and to apparently curl up the outer edge, the exact opposite of what might be expected. It appears almost as if the contracting action which must take place more strongly at the exposed edge of the mirror acts in the greatest degree about two inches in, leaving the extreme edge curled up. This curling up of the edge remains persistent and of about the same extent over about 8 hours exposure to decreasing temperature. The general change in the figure during exposure to the night sky, however, seems relatively small, and it appears that, if the daily rise of temperature could be diminished, the working figure would be much improved.

It will be noted, Tables III and IV, where the figures are given for the separate quadrants, that there is no evidence of astigmatism and that the difference appearing in the test at the optical shop must have been due to stratification and changing temperature gradient in the tube and mirror. Especially in exposure 2 in Table IV, where the mirror except at the very edge must have been nearly normal in temperature, are the differences between the two quadrants very small and quite accidental in character and the general figure, obtained in the tests on May 19 at the principal focus under constant temperature and that in the optical shop at the centre of curvature, agree closely with one another and indicate a remarkably good figure.

The result of these tests then was taken as indicating the necessity of some device, such as the "canopy" used on the Mt. Wilson 60-inch reflector, to diminish the rise of temperature around the mirror during the daylight hours. Considerable thought was given to the best method of accomplishing this. The arrangement of mounting and dome made a suspended canopy impracticable and it was at first planned to make a box in two halves with refrigerator walls, mounted on castors to be rolled up to the tube placed in the vertical position, encircling it and covered over at the top of the closed section by a removable pad of blankets. But these two sections would be unsightly, bulky, cumbersome and difficult to get out of the way when observing.

The plan of placing a permanent insulating cover entirely surrounding the lower closed section of the tube containing the mirror was finally decided on and the encasing of the mirror was made complete by similar permanently placed insulating material at the bottom of the cell and a removable pad of woollen blankets placed on light boards laid over the top of the closed section of the tube. In addition, insulating felt was packed all around the edge and bottom of the mirror so that radiation could only take place from the silvered surface and this, owing to the polish, would be very slow.

The insulating material employed was the cotton felt used in making mattresses. The conductivity of this felt is not much greater than wool and its cost is less than one-fourth. Quilted pads about two inches thick covered with heavy cotton were made of this material and the outer cylindrical sections of the cell and central section of the tube were covered from top to bottom. These pads were covered with a close-fitting cover of khaki-coloured duck laced tightly over the padding, making a permanent and neat looking job. Similar pads were placed directly above the circular metal plates covering the bottom of the cell and the space between these pads and the mirror was completely filled in with the felt. Similarly around the edge of the mirror between it and the cell, pads of the felt were placed above the counterpoise ring extending up to the very edge of the surface while below these pads the space between cell and mirror was completely filled in with the loose cotton.

The mirror and closed section of the tube were now completely encased in insulating material with the exception of the top which, during observing, must of course be open to the sky. As previously stated, this was covered during the day by a removable pad of three thicknesses of the best woollen blankets laid on light boards placed across the top of the central section.

There is hence enclosed within this protective covering 12 tons of steel and 2 tons of glass and the quantity of heat stored there makes the change of temperature within

the insulator very slow. Tests with a thermograph inside have shown that in general the change of temperature around the mirror is only about one-third that in the dome. In practice, as the cover is put on as soon as observing is finished in the morning, slightly above the minimum temperature reached during the night, and as the range inside is about one-third of that in the dome, the mirror is hence, when the dome is opened, usually from 2° to 3° F. below the temperature at the beginning of observing. As the average fall from then until dawn is about 5° F., it is evident that there is never any high temperature gradient between the mirror and the surrounding air, that all except the slowly radiating upper surface is protected by felt and that hence the changes in figure will be slow.

Practical experience has shown that the performance is much improved and that the aberration present in the mirror is generally negligible. Hartmann tests have only been made on two nights since the covers were applied. On September 26, 1918, the general temperature, interrupted of course by the usual daily increase and decrease, had been gradually rising from 52° F. on Tuesday, September, 24 at 6 A.M. to 58° on Thursday, September 26 at 6 A.M. Both Tuesday and Wednesday had been cloudy and when the sun came out on Thursday morning the temperature in the dome rose from 58° at 6 A.M. to $71^{\circ}.4$ at 5 P.M., an unusually large change and a much severer test on the figure than it is normally exposed to. A thermograph placed inside the tube near the mirror had risen from 55° F. on Tuesday at 6 A.M. to 62° F. on Thursday at 7 P.M. when the dome was opened. On being placed outside the tube in the dome it immediately rose 6° showing that the dome temperature was about 6° above that of the mirror. Nevertheless the previous change around the mirror had been slow and, even with this great difference the protection of the felt around edges and bottom and of the silver on the top seemed to keep the change gradual enough to prevent much distortion. Table V, which contains the result of two Hartmann tests on this date, the first one hour, the second two and a half hours, after the mirror was open to the sky, shows that the aberration even under these unusually severe conditions is quite moderate, less than one-half that on the unprotected mirror on May 12 with a much smaller change of temperature, and that the mirror has a good working figure.

Similarly on April 29, 1919, another Hartmann test was made at the principal focus. In this case the temperature during the early morning hours from 3 A.M. to 7 A.M. had been practically constant at $48^{\circ}.5$ F. The insulating cover was not placed over the top until about 10 A.M., when the temperature had risen to 53° F. The mirror was opened to the sky at 9 A.M. to test the collimation of the secondary when the temperature was at $52^{\circ}.3$ and closed and covered at 10 A.M. From then until 6 P.M. the temperature gradually increased to $57^{\circ}.5$ when the dome was opened. When the mirror was uncovered at 7 P.M. the dome temperature was $55^{\circ}.5$, at 8 P.M. $54^{\circ}.0$, at 9 $53^{\circ}.8$, and from 10 P.M. until 1 A.M. remained practically constant around $53^{\circ}.0$. Hartmann tests were made at the Cassegrain focus between 9.35 and 10.15 and at the prime focus between 12.00 and 12.45. The results of the latter, also given in Table V, show a very good working figure.

TABLE V ZONAL TESTS SEPTEMBER 26, 1918, AND APRIL 29, 1919.

FOCI IN MILLIMETRES.

Radius of Zone	Sept. 26, 1918 Foci at Exposure 1			Exp. 2	Foci on April 29, 1919			Differences of Focus		
	Quad. 1	Quad. 2	Mean		Quad. 1	Quad. 2	Mean	Sept. 26, 1	Sept. 26, 2	Apr. 29
in.										
35	33.52	33.90	33.71	33.90	29.80	29.96	29.88	0.00	0.00	0.00
33	33.69	33.82	33.75	34.02	30.45	30.16	30.30	0.04	0.12	0.42
31	33.82	33.41	33.61	33.92	30.34	30.18	30.26	-0.10	0.02	0.38
29	33.59	33.68	33.63	33.70	29.83	30.34	30.08	-0.08	-0.20	0.20
27	33.64	33.74	33.69	34.10	30.22	30.25	30.23	-0.02	+0.20	0.35
25	33.90	34.34	34.12	34.28	30.49	30.39	30.44	+0.41	0.38	0.56
23	34.23	34.01	34.12	34.57	30.28	30.82	30.55	0.41	0.67	0.67
21	34.09	34.16	34.12	34.67	30.34	30.66	30.50	0.41	0.77	0.62
19	34.69	34.60	34.64	34.92	31.19	30.79	30.99	0.93	1.02	1.11
17	34.51	34.89	34.70	35.10	30.49	31.03	30.76	0.99	1.20	0.88
15	34.85	34.76	34.80	35.04	30.71	31.09	30.90	1.09	1.14	1.02
13	35.61	34.15	34.88	35.63	31.24	30.95	31.09	1.17	1.73	1.21
11	35.58	35.81	35.69	36.54	30.80	31.84	31.32	1.98	2.64	1.44

The results of these tests are also shown graphically in Fig. 8 where the ordinates represent the positions of focus in millimetres, the scale being indicated on the figure, of the various zones shown as abscissae, the edge of the mirror being at the left. The cross-sectioned parts at the bottom represent the relative positions of principal and Cassegrain mirrors.

The straight line at each curve represents the weighted mean position of best focus, taking account of the relative areas of the different zones. Distances from this line to the curve represent the deviations of the foci for the different zones, above the line longer focus, below the line shorter focus.

The change from the shop test at constant temperature to that of May 12 where practically the maximum range at Victoria was present is very marked as is also the great improvement when the temperature change was very small on May 19. After the insulating cover was applied the effect of the greatest probable temperature change is shown by the test of September 26, while the figure under average working conditions probably closely approximates that of April 29, 1919.

There seems no doubt that the introduction of the insulation has markedly improved the performance, reducing the aberration to nearly one-third of the former amount. There further seems no doubt that rising temperature produces positive aberration, falling temperature negative aberration, that the amount and the rapidity of the change is dependent on the temperature gradient, but that in no case, with the temperature changes taking place at Victoria, will the mirror be distorted sufficiently (since the insulation has been applied) to appreciably affect the definition.

If we compute the circle of confusion arising from the zonal aberrations at constant temperature, considering only the geometrical theory, the diameter will be approximately

0.025 millimetre, 0.001 inch, only a fraction of the diameter of the tremor disc caused by atmospheric disturbances. Similarly, if the departure from the paraboloidal form due to a zonal longitudinal aberration of 0.25 millimetre for a zone 19 inches radius and 2

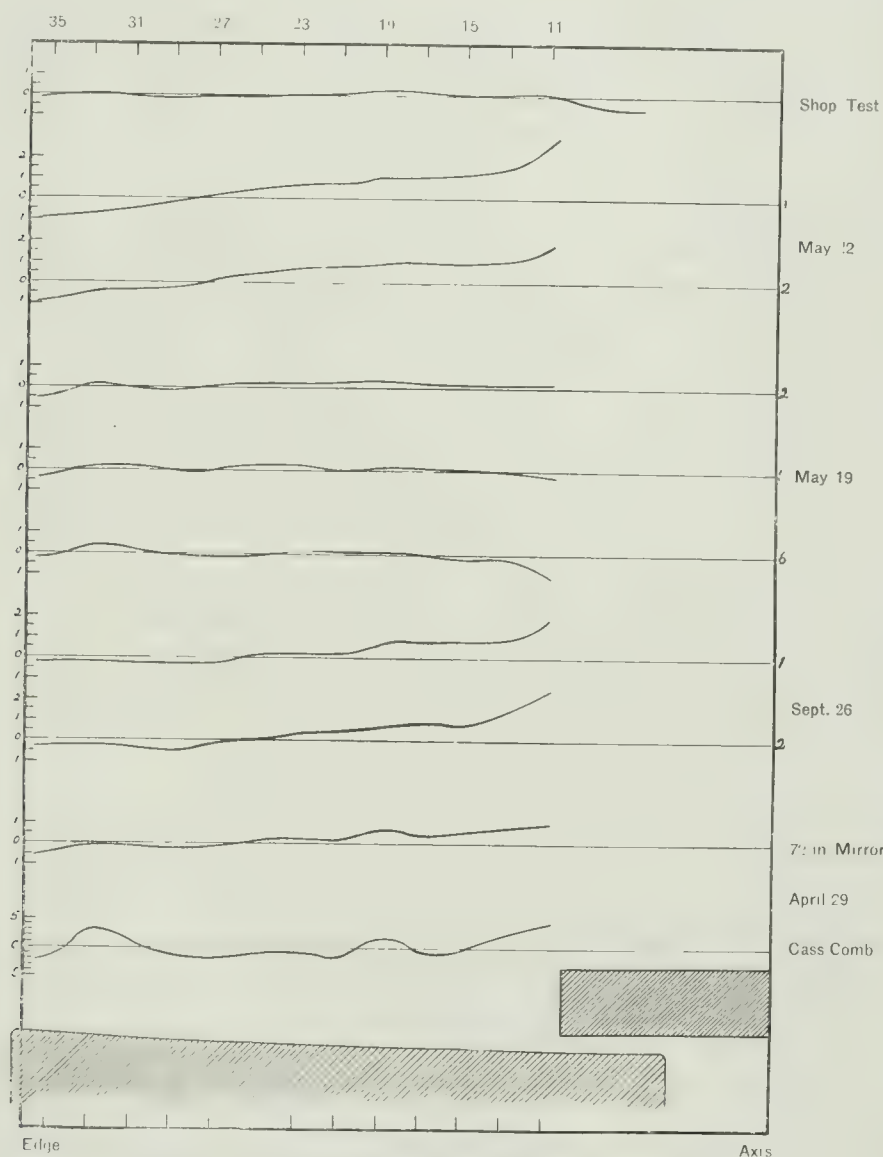


Fig. 8. Graphical Representation of Zonal Aberrations.

inches wide be computed, we find a deviation of the surface from the true form of about one-eighth of a wave, considerably within the theoretical limits of the quarter wave required to give good definition.

The mirror, as the tests show and as its use has proved, has a remarkably fine figure. The telescope has not yet been used much at the principal focus of the main mirror and only a very few direct photographs have been obtained. These few, however, are sufficient to show that the star images are very small and sharp, when the seeing is good

the minimum diameter being only slightly over one second of arc, and that beautiful photographs of nebulae and clusters can be obtained. No zonal measurements that I am aware of have been published for any other large mirror but the 100-inch, where the maximum deviation was 0.15 millimetre, somewhat smaller than the 72-inch, but the much greater relative stiffness and thickness of the latter will probably enable it to withstand the changes of temperature encountered under observing conditions much better.

The Brashear Co. are to be congratulated on producing such a fine surface under such difficult and trying conditions and it is only right that I should express my appreciation to them collectively and individually for their successful efforts. The presence of the hole in the centre of the mirror doubled, according to their estimate, both the difficulty and the time of figuring. Towards the last the tremendous pressure of war orders, with the difficulty of getting suitable optical glass, and the uncertainty as to how long it would take to complete the mirror made the figuring, always a nervous strain, doubly trying. I am glad to take this opportunity of expressing my appreciation of their persistence with the work until their efforts were crowned with such notable success. Dr. Brashear himself, although of late not participating actively in the optical work, was much interested in this surface and not only prepared all the tools but rough and fine ground and polished the mirror. Many of the methods of handling and testing are due to his ingenuity. The burden of the figuring was, however, taken by Mr. James B. McDowell, the secretary and manager of the company, ably assisted by his chief optician, Mr. Fred. Hagemann. It is due to Mr. McDowell's skill and persistence in the face of difficulties that the surface was finally brought to such a satisfactory finish. Much of the figuring was done by him personally, and although at the last his other duties were too pressing to permit of this, he always tested after working and decided on and directed Mr. Hagemann as to the next stage. The final touches were given by Mr. Hagemann, who by great skill in local polishing as it was not possible to get the figure by large tools, gradually brought the surface to the accuracy given by the tests and at the same time maintained its smoothness and regularity of figure.

I am convinced, after their experience and success with such a large and difficult piece of work, no one need be uncertain as to the outcome and quality of any optical work entrusted to them.

As previously mentioned, the figuring of the Cassegrain mirror required about a week's work by Mr. McDowell. Owing to the relatively small size of the auxiliary plane, its aperture being only 0.46 that of the principal mirror, less than one-half the diameter, one-fourth the surface of the Cassegrain, could be seen when the knife edge test was made. It was consequently not an easy matter to determine exactly what the shadow figures produced in this test represented nor what should be done to the mirror to improve them. Nevertheless, the skill and experience of Mr. McDowell overcame the difficulties and the secondary was declared completed after a week's figuring.

Evidently no Hartmann test of the combination could be carried out with a parallel beam only 33 inches in diameter and as there was a provision in the contract requiring the refiguring of the Cassegrain by the makers, if found desirable after the test of actual use, I had no hesitation in accepting this mirror.

The relative smallness of the star images given by the combination, considering the great equivalent focal length of 108 feet, made it evident that the figure of the Cassegrain must be good and no tests were made until January, 1919. The same zone plate was placed over the principal mirror, the telescope turned to α Persei, then not far from the zenith, and exposures made on small plates inside and outside the focus. When plates inside the focus were obtained, the image was focussed on the spectrograph slit and the appearance of the zonal images could be examined by the auxiliary telescope used for visual observations and the plate rested on the reflecting prism cell on the end of this telescope for making the exposures. When outside the focus, and this effect was produced by changing the position of the secondary mirror, raising it until it was approximately in focus in the visual telescope, the appearance of the extra focal image could be observed in the spectrograph guiding telescope, the plate placed on the slit cap and the exposure made. The separation of the position of the two exposures was determined from the measured separation of any pair of zonal images, the distance apart of the corresponding openings in the zone-plate, and the known focal length, 108 feet, of the combination. The separation required, owing to the comparatively large size of the zonal images, was large, about 400 millimetres, as compared with about 60 at the principal focus. The diffuse character of the images was probably due to the apertures in the zone-plate being too small for the increased focal length, resulting in an increase in diffractive spread and rendered the plates difficult to measure with some loss of accuracy. However, the mean of two sets of measures of January 6 and of two sets on April 29 had fair interagreement as seen in Table VI and the final results probably represent the figure very closely. As is evident from a comparison of the results at the principal and Cassegrain focus on April 29 obtained from Tables V and VI and exhibited graphically in the two lower curves of Fig. 8 the aberrations in the two cases are quite similar and it is evident that the Cassegrain mirror reproduces and magnifies, even when reduced in scale corresponding to the relative focal lengths as has been done in the figure, the aberrations of the principal mirror. Unfortunately on January 6 no test was made at the principal focus and the figure of the principal mirror can only be surmised from that of the combination.

Nevertheless, the deviations which occur and the increase of relative aberration with the combination, which are in just the positions and of the order that would be produced if the correction of the secondary had not been carried sufficiently far, indicate a possibility of improvement. If the convex curve of the secondary were made a little flatter in the zone corresponding to a radius of 30 to 34 inches on the principal mirror, and also nearer the centre for zones on the principal mirror from 11 to 20 inches radius the figure would probably be improved but whether the actual images would be better and the spectrographic exposure time appreciably diminished is questionable. Normally, owing to atmospheric disturbance with such a large aperture and great focal length, the image is much larger than that due to the amount of aberration present and improvement in the figure now already very good would make little difference. In the not frequent instances when the "seeing" is very good there might be some improvement but as at these times practically the whole visual image disappears in the slit opening, which is about 0.3 seconds wide, probably also the exposure would not be much shortened.

TABLE VI—ZONAL DIFFERENCES OF FOCUS OF CASSEGRAIN COMBINATION

	January 6			April 29			Aberrations Cass.		Aberrations Prin. Mirror Apr. 29
	1	2	Mean	1	2	Mean	Jan. 6	Apr. 29	
35	9.18	10.35	9.76	1.13	1.65	1.39	-1.06	-1.79	-0.46
33	10.11	13.70	11.90	5.85	6.73	6.29	+1.08	+3.11	-0.04
31	8.76	11.67	10.21	4.41	4.59	4.50	-0.61	+1.32	-0.08
29	7.45	10.40	8.92	1.87	2.02	1.94	-1.90	-1.24	-0.26
27	7.13	10.07	8.60	1.10	1.50	1.30	-2.22	-1.88	-0.11
25	8.27	11.20	9.73	2.04	2.58	2.31	-1.09	-0.87	+0.10
23	9.69	12.67	11.18	2.68	2.51	2.59	+0.36	-0.59	+0.21
21	9.58	12.86	11.22	1.46	2.15	1.80	+0.40	-1.38	+0.16
19	11.67	14.87	13.27	4.63	5.33	4.98	+2.45	+1.80	+0.65
17	11.53	15.11	13.32	2.44	3.19	2.81	+2.50	-0.37	+0.42
15	13.25	16.50	14.87	2.04	3.91	2.97	+4.05	-0.21	+0.56
13	13.93	17.77	15.85	5.87	5.03	5.45	+5.03	+2.27	+0.75
11	15.12	21.26	18.19	8.27	6.28	7.27	+7.37	+4.09	+0.98

The test of actual use has shown that the images must be very good indeed for the spectrographic exposures are relatively short. The exposure times required depend upon the "seeing" to a much greater extent than is the case with a smaller telescope. At Ottawa with the 15-inch telescope of about 19 feet focal length, "seeing" conditions, provided there was no haze or cloud, had little effect on the exposure time, an increase of about 50 per cent being the maximum required in poor "seeing". At Victoria where the aperture is 72 inches and the focal length 108 feet, nearly 6 times that at Ottawa, the image for any disturbance becomes relatively much more enlarged and in very bad "seeing", fortunately very rare, the exposure times may be as much as 4 or 5 times the normal required in fair "seeing".

The spectrograph, which is now being used with one prism and a medium focus camera, gives a linear dispersion at $H\gamma$ of about 35 Å per millimetre. In good "seeing" a well exposed spectrogram of a star of photographic magnitude 7.0, with a slit width of 0.05 millimetre, 0.3 seconds at the Cassegrain focus, can be obtained in 20 to 25 minutes. If the star is of type A or B with only broad hydrogen or helium lines, it is generally found desirable to give about 50 per cent more exposure, making the spectrum wider and stronger, in order to render the measurement more easy and accurate. A star of 6.0 photographic magnitude at Ottawa required about 2 hours exposure, from 12 to 15 times that required at Victoria. It has usually been considered owing to the atmospheric disturbances, "tremor disc" conditions, that as the aperture is increased the best that can be hoped for, so far as decrease in exposure time is concerned, is that the gain may be proportional to the ratio of apertures not areas. In these two cases the ratio of apertures are as 4.8 to 1 and of areas as 23 to 1. The gain in exposure time is about three times the ratio of apertures and one-half the ratio of areas, a remarkably favourable showing when the great focal length and consequent increase in linear scale of the image is considered. I believe, if as efficient a spectrograph could be placed at the focal plane, that owing to

the smaller linear scale of the star image as well as to the superior optical properties of the main mirror over that of the combination, spectrograms with exposures nearly inversely proportional to the areas could be obtained

There can be no doubt that although it might be possible to theoretically improve the figure of the Cassegrain, it is questionable whether much practical improvement so far as shortening the exposure time on spectrograms would be effected. There is further no doubt that the effect of the ordinary temperature changes on the figure of the combination which, though undoubtedly chiefly acting on the principal mirror, yet the aberrations produced therein are magnified by the secondary, give deviations of greater magnitude than those produced by the under-correction of the Cassegrain. And even the influence of these temperature effects is entirely overshadowed by the increase in size of image produced by even a slight falling off in "seeing" conditions.

The Newtonian mirror which is the same size as the Cassegrain, 19.5 inches diameter, 3.25 inches thick, was tested in the usual way at the optical shop and indirectly tested by the Hartmann method during the process of testing the 72-inch. For some of the zonal test plates were made at the Newtonian focus and some with the flat removed, directly at the principal focus and no effect whatever of the presence of the flat could be seen in any difference or deviation produced in the measures. It is of course self-evident, as no magnification is given by the flat, that any deviations of figure will have only one-fourth the effect on the image that they have in the Cassegrain and, as the flat is undoubtedly correct within less than a quarter wave, its figure is practically perfect.

In order to be able to make visual observations at the Cassegrain focus without removing the spectrograph, which would mean considerable loss of time on Saturday nights when the public have the privilege of observing with the telescope, a special observing telescope was designed. This telescope has a reflecting prism of 2 inches aperture at its inner end, a symmetrical triplet objective of $2\frac{1}{2}$ inches aperture $12\frac{1}{2}$ inches focus midway, with conjugate foci at prism and ocular, and the ocular at the outer end of the tube. This telescope screws, perpendicular to the optical axis, by bayonet joint into an opening in the side of the spectrograph frame above the slit, and can be attached and detached in a moment. The image formed on the upper face of the prism is transferred by the triplet to the focal plane of the ocular and can be observed there just as if the ocular were directly in the axis. The focussing of the image is effected as previously indicated by moving the secondary in and out by a hand wheel close to the visual ocular and to the guiding telescope of the spectrograph.

A full set of special three-lensed oculars from 0.25 inches to 4 inches focus, those longer than 1 inch having field lenses of from 2 to $2\frac{1}{4}$ inches aperture are provided and these are arranged to be conveniently used at either the principal, Newtonian or Cassegrain foci.

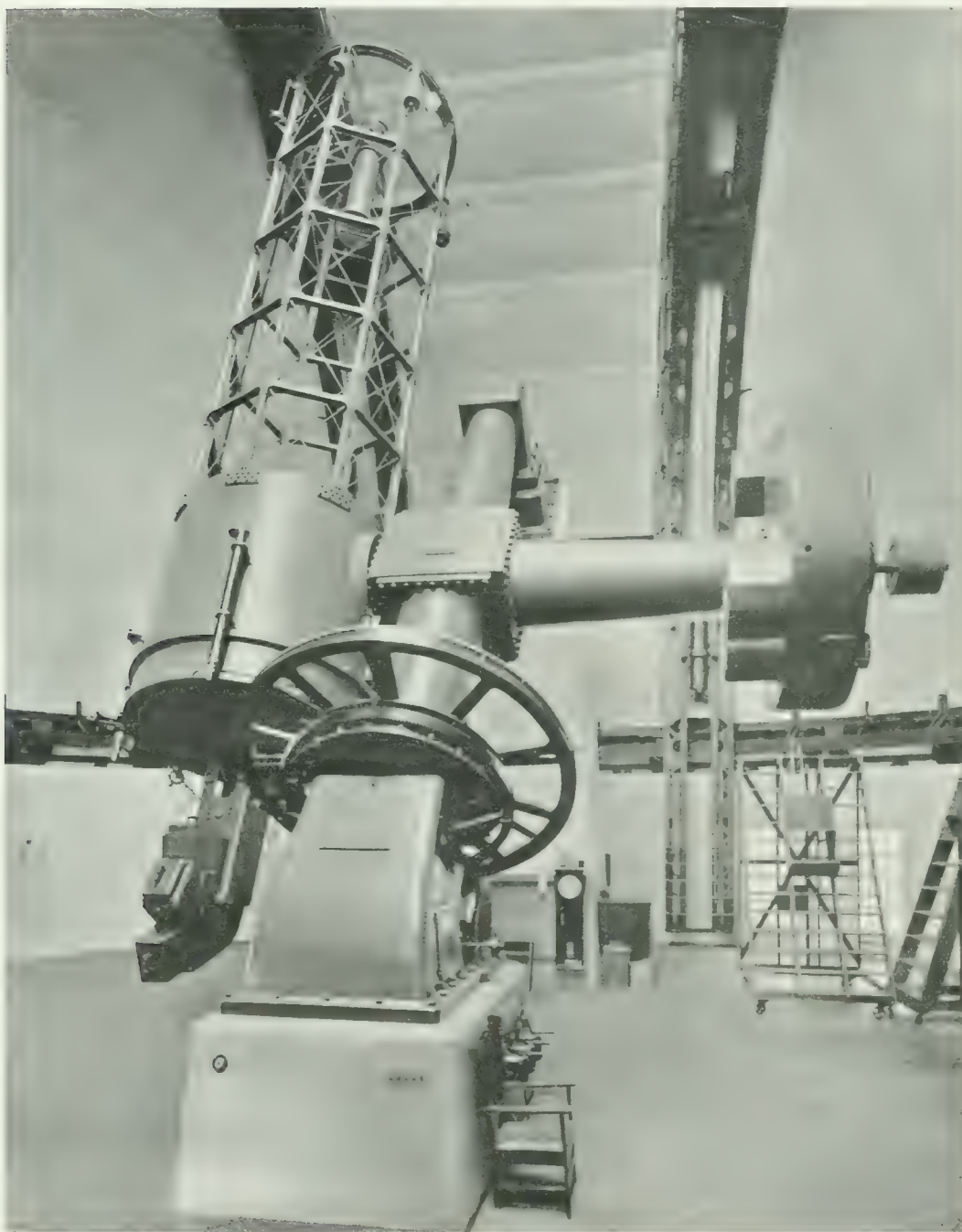


Fig. 9. Telescope from South—Tube West of Axis.

CHAPTER VI. DESCRIPTION OF THE MOUNTING

The mounting of the 72-inch telescope is similar in its general features to that of the Melbourne 4-foot, the Ann Arbor 37-inch and the Crossley 36-inch reflectors. It consists essentially of a long polar axis mounted on separate piers, the declination axis crossing the polar axis about midway, with the tube on one side and the housing containing the mechanism for moving the tube in declination on the other. A good idea of the general form of the mounting can be obtained from the illustrations, Figs. 9, 10, 11 which well show the harmonious and well balanced proportions of the design.

THE TUBE

The tube of the telescope is in three sections, the central section which is attached to the declination axis, the lower section or mirror cell which carries the principal mirror, and the upper section or skeleton tube which carries attachments for use at the prime focus and for holding the Newtonian or Cassegrain mirrors.

The central section of the tube is a large heavily ribbed steel casting of cylindrical form with a large boss 41 inches diameter near the upper end of the cylinder to which a flange on the end of the declination axis is firmly bolted. This steel casting which weighs 7 tons and is exceptionally solid, homogeneous and thoroughly annealed, is 7 feet 4 inches outside diameter, 6 feet 1½ inches high, has a flange 7 feet 10 inches diameter at the lower end to which the mirror cell is bolted and another internal flange at the upper end to which the skeleton tube is firmly attached. These two flanges were turned perfectly parallel and concentric and the boss, to which the declination axis is attached, bored and faced at right angles to these flanges in one of the large boring mills at the Bethlehem Steel Works where this and the other large steel castings were made and machined. Both the castings and the machine work are of the highest grade and contribute greatly to the success of the mounting.

Near the lower end of this central section is placed the shutter whose purpose is to tightly enclose the mirror and protect it from dust and moisture. It consists of 12 sector shaped steel leaves attached at their bases to 12 short shafts which rotate in bearings spaced around the periphery of the lower end of the centre section. These 12 shafts are connected together by universal joints and a worm wheel firmly keyed to one of them can be rotated by a worm and shaft geared to a handwheel at the lower end of the mirror cell. By turning this handwheel the 12 leaves can be quickly raised and lowered simultaneously. As the sharp edge of one leaf dovetails into a V-shaped groove in the adjacent leaf perfectly tight joints are formed. When closed down, these leaves are not flat but stand at an elevation of about 30° in the centre. They hence make an immensely strong arch and form a perfect protection for the mirror surface against any accident or falling body.

The mirror cell, also an annealed steel casting, of the same diameter as the central section, is bolted to the latter through the common flange by 16 bolts. It has radial and concentric ribs, cast integral with the cylindrical part, on which are mounted the



Fig. 10. Telescope from South--Tube above Axis.

bottom supports of the mirror. These consist of 12 circular pads of open section about 12 inches in diameter the circumference about $1\frac{1}{2}$ inches wide being faced with cork and bearing against the back of the mirror. These twelve pads are so distributed that each supports its proper proportion of the weight of the mirror. Three of them are rigidly connected with the ribs of the cell by a screw adjustment which enables the mirror to be collimated in the tube. The remaining nine are counterbalanced by levers and weights so designed that each sustains one-twelfth of the resolved weight of the mirror whatever the position of the tube. These twelve pads hence maintain the mirror in collimation along the axis of the tube and at the same time so support and float it in the cell that no chance of flexure exists.

For collimation and support perpendicular to the axis a similar counterbalancing system is provided. A large ribbed bronze ring lined with cork surrounds the edge of the mirror midway. This ring is in four sections and can be adjusted by liners between the sections so as to just fit without strain. At twelve equidistant positions around this ring are attached twelve weighted counterbalancing levers also so designed as to exactly support the resolved component of the weight of the mirror perpendicular to the axis. Hence the mirror is floated in the cell without strain or tendency to distortion in every position. It is maintained in position laterally by four blocks, 90° apart. Two adjacent ones are fixed to the cell while the opposing two maintain the mirror in contact with the fixed blocks by means of springs, which, as the whole weight of the mirror is supported by the counterbalancing ring, need only exert slight pressure. This method of counterbalancing is similar to that employed by Ritchey with the 60-inch Mt. Wilson telescope, and, although the weakness of the material in the 100-inch necessitated another form of edge support, I believe the one here is much more suitable for the 72-inch mirror and it certainly seems to work beautifully. Four safety blocks firmly attached to the cell are provided so that the mirror can not fall forward in case the tube becomes depressed below the horizontal.

At the lower side of the cell, which, with the exception of a central aperture the same size as the hole in the mirror, is entirely covered with a sheet steel plate, is attached a solid cast iron ring about 30 inches diameter which can be rotated around the axis, by means of a worm gearing into teeth cut in the periphery, to any desired orientation, read on a graduated circle. To this ring the spectrograph or any other attachment such as the double slide plate holder can be attached and oriented as desired.

The upper or skeleton section of the tube is built up of structural steel. It is an octagonal prism 7 feet 4 inches outside diameter and 23 feet 4 inches long, fitted with a 3-inch circular channel at top and bottom, the four intermediate sections being octagonal and built up of 3-inch I-Beams. The main members which extend uninterruptedly the whole length are eight 3-inch I-Beams. These main members are firmly connected to the top and bottom channels and to the intermediate sections by steel tee and cross-shaped plates inside and out firmly rivetted to the channels and I's. The heavy T-shaped plates at the bottom are securely bolted to the central section both inside and out, further security at this vital point being obtained by bolts through the channel and corner steel castings.



Fig. 11. Telescope from North-west—Tube East of Axis.

The design of this tube is a marked improvement over any other reflector skeleton tube in the original method employed of rendering it exceedingly stiff and rigid. It is undoubtedly relatively lighter and at the same time stiffer than any hitherto produced. It has besides the further advantage that it is entirely composed of commercial shapes and is hence of comparatively inexpensive construction. The method employed is that of diagonal tension rods, every one of the 40 rectangular sections being diagonally cross-connected by steel rods in which any desired tension may be obtained by right and left hand threads. These rods are each screwed up to a tension of about 2,000 pounds so that the whole tube is under tension, even the lower members when in horizontal position, and is hence exceedingly stiff for its weight. The total weight of the skeleton portion is 3,740 pounds and the deflection, even with the 300-pound Cassegrain in place, is very small. The general design and construction can be readily obtained from Fig. 12 and from the various illustrations of the completed telescope.

The arrangement at the upper end of the tube by means of which changes may be made of attachments for work at the prime focus, at the Newtonian focus or with a Cassegrain mirror are one of the special features of the telescope and are such a decided advance over existing methods as to merit a detailed description.

In all previous reflecting telescopes, the practice followed has been to make the tube somewhat shorter than the focal length of the mirror, and to mount each of the attachments on a separate cage or extension of the same diameter as the tube. To change from Cassegrain to Newtonian for example, as the Cassegrain mirror is mounted considerably lower than the Newtonian mirror, it would be necessary to unbolt the short Cassegrain extension, lift it off the end of the tube and replace it with the longer Newtonian cage. In a 72-inch telescope these cages would weigh considerably over half a ton, would be cumbersome, difficult and dangerous to handle, upsetting the balance of the telescope both in declination and right ascension. Indeed I understand the practical experience has been that such change can not be made under less than two or three hours, which practically prohibits it from being done during observing hours.

To Mr. Swasey's mind, a method of changing mirrors weighing only 80 lbs. which required the moving of two awkward pieces weighing say 1,500 lbs. seemed especially unworkmanlike and cumbersome. He suggested therefore that a method be developed by which only the mirrors and cells need be interchanged, the tube remaining always the same length and serving, when both mirrors were removed, for direct work at the prime focus.

By co-operation between the writer and Messrs. Burrell and Fecker, the present method was worked out, which possesses all the advantages of permanency of adjustment of the various attachments without any of the inconvenience, difficulty and delay entailed by the removable cage extensions hitherto employed.

The principle employed is well shown in the illustrations, Figs. 12, 13. The tube is of a fixed length such that the focus of the main mirror is about 6 inches above its upper end. The circular channel which forms the upper member is reinforced and stiffened by a flat ring of steel $\frac{3}{8}$ -inch thick, 76 inches in internal diameter and 7 inches wide. This has bevelled edges, is faced true with the axis and to it can be clamped and rotated to any desired position the guiding and viewing eyepiece and the rods for operating the

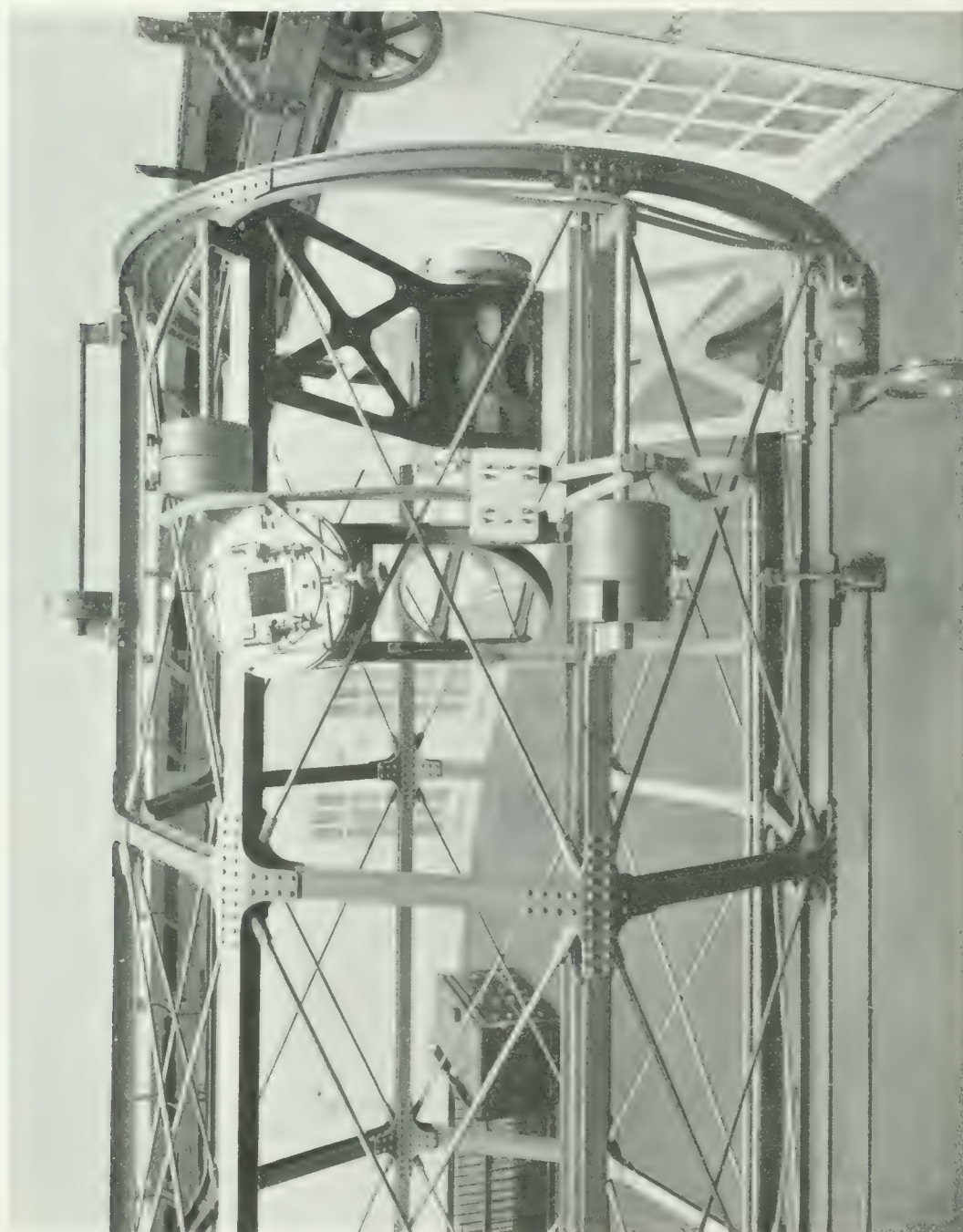


Fig. 12. Photograph of Upper End of Tube—Plate Holder and Newtonian attached.

double slide plate holder when it is placed in the prime focus. This latter and the Newtonian and Cassegrain mirrors are attached to and held rigidly and centrally by a central aluminum casting about 20 in. long and 14 in. diameter, of circular section which is attached to four of the main members of the tube by four thin perforated webs of sheet steel placed edgewise so as to obstruct little light. These webs, although thin, are deep and attached to the tube by screw adjustment which enables the aluminum casting to be adjusted and rigidly held concentric with the axis of the tube. On the lower edge of this casting is a flange provided with winged nuts on hinged bolts by means of which either Newtonian or Cassegrain is rapidly clamped in position. An inner tube sliding in the upper end of the aluminum casting is movable up and down by an ingenious and smoothly working focussing and self-clamping ring and to a flange on the upper end of this tube the double slide plate holder, or if desired, a focal plane spectrograph, is attached by four hinged bolts with wing nuts. The plate holder is hence held concentrically perpendicular to the optical axis and can readily be focussed by the rotating ring which is graduated so that the focal position can be accurately read off or replaced. The plate holder may be left in position if desired, as it in no way interferes with the use of the telescope in Cassegrain form, and all that is necessary to change from work with the Cassegrain to photography at the prime focus is to remove the Cassegrain attachment, and vice versa, the device for performing this operation to be presently described.

The Newtonian mirror which has a clear aperture of 19 inches is held in a simple cast iron cell, attached at an angle of 45° to a bronze tube, the latter being rotatable in an external tube, a flange on the latter attaching to the flange of the central aluminum casting. A spring stop fixes the Newtonian mirror so that the image is formed in any one of four positions 90° apart around the sides of the tube. The double slide plate holder is held on the end of a flanged focussing tube which slides to approximate position in a simple tubular adapter bolted to any one of these four positions. Final focussing and the perpendicularity of the plate to the optical axis is obtained by three micrometer head focussing screws in the flange by means of which the plate holder may be finally adjusted. The bronze tube holding the Newtonian is comparatively short, about 2 feet long, as the centre of the mirror is only about 4 feet below the principal focus.

When we come to the Cassegrain mirror, which is situated about 7 ft. 2 in. below the principal focus, it is evident that a longer attaching tube is required, the total length being about 5 feet. Instead of being a drawback as would be expected, this is rather an advantage. It is necessary not only to move this mirror longitudinally for the focussing of the secondary image below the principal mirror, but also to collimate it so that its axis may coincide with the axis of the principal mirror. The focussing must be possible without disturbing the collimation and hence the mirror cell is attached to the lower end of an inner tube which can be moved up and down in an intermediate tube by a screw, this screw being connected by shafts and gearing to a handwheel on the lower side of the mirror cell, convenient to the observing oculars. A very smooth slow motion is imparted to this inner tube by turning this hand wheel. The secondary image moves about twelve times as fast as the secondary mirror and hence the image on the slit of the spectrograph or in the observing ocular can be readily and accurately focussed. This inner tube, which carries the mirror, moves in an intermediate tube rotating around a

spherical seat at the lower end and can be adjusted until the mirror is exactly in collimation by two pairs of opposing screws with lock nuts placed at the upper end. Once this collimation is obtained neither the focussing nor removal and replacement of the attachment will alter it. The intermediate and inner tubes are held in a fixed outer tube a flange on the upper end of the latter enabling it to be readily attached to and detached from the central support, while the lower end is supported and flexure prevented by four thin adjustable stay rods in line with the supporting webs in order to offer no additional obstruction to the incident light. The length of this tube allows a long bearing for the focussing and collimating motions thus rendering them sensitive and accurate.

The method of interchanging Newtonian, Cassegrain or prime focus attachments is very simple and expeditious. The dome with the observing platform in its normal or lowest position is rotated to the east, the telescope turned until the upper end of the tube rests on the platform where it is lashed down with a piece of rope. A small traveller carrying a quarter ton differential block at its outer end, is slipped on an auxiliary I-beam permanently attached to the main member of the tube which is uppermost in its present position. If the Cassegrain attachment, which weighs about 300 lbs., is to be attached to the tube, a pin connects the pulley block to the correct position on the attachment which can now be lifted to the correct height by the block and the traveller carrying it slid in the end of the tube. All that remains is to lower into position, push in the swivel bolts and clamp the nuts, then push in the four stay rods which stiffen the outer or lower end of the tube near the mirror and connect the focussing shaft. The whole operation or the reverse one can easily be performed in fifteen minutes. Balance is restored by removing or replacing six weights at the upper end of the tube, no change being needed at the lower end nor in right ascension. The handling of the Newtonian mirror is effected in the same way but is even simpler as this attachment only weighs about 200 lbs. All these attachments and the extra weights are kept on the observing platform as can be seen in Fig. 13 which shows the Newtonian hoisted into position on the traveller, ready to be rolled into position in the tube, while the Cassegrain attachment is on the platform floor in the lower part of the figure.

THE DECLINATION AXIS, BUSH AND HOUSING

The total weight of the tube is approximately 15 tons and it is carried by the declination axis, a gun steel forging $15\frac{1}{2}$ inches in diameter, $14\frac{1}{2}$ feet long having a flange at one end 41 inches in diameter and 4 inches thick which fits into and is securely bolted to the boss on the central section of the tube. This axis weighs over $4\frac{1}{2}$ tons and is carried in ball and ball thrust bearings, which will be later described, at the two ends. The declination axis passes through the cubical central section of the polar axis at right angles to it and extends through and is carried at the outboard end by a conical tubular steel casting, which may be called the declination bush, which is bolted to the cubical section of the polar axis. At the outer end of this bush a circular casting about 9 ft. in diameter and 2 ft. deep is bolted which serves the two-fold purpose of helping to balance the weight of the tube on the opposite side of the polar axis and of forming a supporting base for the mechanism required to turn the tube in declination both in quick and slow motion. The



Fig. 13. Method of Changing Mirrors.

declination axis carries at its outer end and within this housing a large spur gear 8 ft. in diameter firmly keyed to it, which serves to move the axis and hence the tube in the quick motion in declination. Outside of this spur gear is the declination circle 8 feet in diameter and graduated in degrees. Counterweights for balancing in right ascension are screwed on a bronze cased extension of the declination axis.

THE POLAR AXIS

The polar axis is in three sections, a central cubical section 3 ft. 8 in. a side and upper and lower conical tubular sleeves which have square flanges on the inner ends securely bolted to the central section. These are all steel castings of the highest grade and thoroughly annealed. The outer ends of the upper and lower sleeves have forged steel pivots forced into them which serve to carry the ball bearings on which the axis rotates. The assembled axis which is 21 ft. long and weighs $9\frac{1}{2}$ tons was turned up as a unit, ensuring true concentricity of all the bearings, and was not afterwards separated but handled as one piece. Mounted on ball and ball thrust bearings on the axis near the lower end is the driving worm wheel 9 ft. in diameter and below this is keyed the quick motion spur gear 6 ft. in diameter and the hour circle graduated to 5 minutes of time. Fig. 2 shows the polar axis with these wheels and the radial ball bearings attached ready to be lifted into place between the upper and lower pier heads.

THE NORTH PIER HEAD

This consists of two parts of cast iron weighing together $5\frac{1}{4}$ tons, the pillar block which is bolted to the concrete pier and the bearing head which is movable and carries the bearing for the north end of the axis and which is attached to the pillar block by push or jack screw and holding down bolts. By these screws and bolts the correct elevation of the polar axis can be obtained. The bearing head is also movable sideways so as to enable the axis to be placed exactly in a north-south direction.

THE SOUTH PIER HEAD

This is a single iron casting of the shape well shown in the figures and weighs 7 tons. It carries the ball and ball thrust bearings of the lower end of the polar axis and within it is the mechanism for the quick motion in right ascension to be presently described. The driving clock although it may appear part of the pillar head is an independent unit resting on and adjusted from a separate base plate.

THE DRIVING MECHANISM

The telescope is driven in right ascension at the sidereal rate by the regular worm wheel, worm, and weight driven governor mechanism generally called the driving clock. Although of the well known and efficient Warner & Swasey form there are some novel and valuable modifications from the standard type which add much to its accuracy and convenience.

The worm and worm wheel are probably the parts of the driving mechanism requiring the greatest care in construction as any inaccuracy in either produces a most annoying irregularity in the following. The worm which is $3\frac{1}{2}$ inches in diameter of $\frac{1}{2}$ -inch pitch, the thread being 9 inches long of which only 4 inches of the central part is used, is of the best tool steel thoroughly annealed, was rough milled and then finished—turned most carefully. It was then ground in a long nut to remove any periodic error and finally lapped until a fine-bearing surface was obtained.

The worm wheel is a semi-steel casting with a bronze rim, in which the teeth are cut, shrunk on. Its diameter is 9 feet and it runs free on the polar axis rotating on two radial ball bearings while the end thrust is taken by a ball thrust bearing. It weighs complete nearly 2 tons and when mounted on its bearings, it takes a pull of 2 lbs. at its periphery to start it and $\frac{1}{2}$ lb. to keep it rotating.

After the worm wheel had been bored and turned as true as possible on a boring mill, it was mounted on its own bearings on a heavy cast iron pivot of the same diameter as the section of the polar axis on which it is placed. This pivot was mounted on one end of a long bed on the other end of which was a gear cutter head rotated by an electric motor. The worm wheel was rotated by hand and a fine cut taken off the bottom and top of its rim and on its periphery to make it perfectly true. On the upper flanged hub of the worm wheel, a 42-inch cast iron circle was clamped. This circle had a strip of silver inlaid in it which was divided on the very accurate Warner & Swasey dividing engine to half degree spaces. Two micrometer microscopes were firmly mounted on the pivot and the circle was accurately centred and clamped. It was now ready for indexing and cutting the teeth in the rim. The gear cutter head was set at the proper helix angle, the wheel rotated until two of the half degree divisions were exactly bisected in the microscopes and a tooth cut. This was repeated until the whole 720 teeth were roughed out. In order to prevent inaccuracies due to springing or heating, the wheel was cut three times around. After cutting, the driving worm in its box was bolted to the bed and worm and worm wheel were run together with rouge and oil for nearly a week which gave a fine smooth bearing on all the teeth. Undoubtedly this process produced a very perfect worm and worm wheel as no trace of periodic error or other irregularity in driving can be detected when the telescope is set on a star.

The driving clock proper is similar in design to the driving clocks on the Lick and Yerkes telescopes but has several improvements. The principal one is the addition of the slow motion mechanism on the principal driving shaft, thus doing away with the heavy, cumbrous slow motion arm in right ascension and with all possibility of backlash in guiding. Another advantage lies in making the connection between the main drive shaft and the worm wholly by spur gears instead of by bevel gearing, by which periodic error is likely to be introduced, as in other driving clocks. The clock is built as a separate unit, enclosed in a dust proof case, and rests on a cast iron base bolted to the main pier. The clock case is adjusted exactly in position on this base by adjusting and holding down screws. The worm is carried on an adjustable slide on the south pier head and in adjusting the clock all that is necessary is to bring it up until the intermediate spur gear, which communicates the motion from the main drive shaft to the worm, is in

correct mesh with the pinion on the worm. The winding drum and clock gears occupy the upper half of the clock casing while the governor or pendulum is in the lower half. The governor is of the standard Warner & Swasey type and revolves once per second. This speed is reduced by the gearing so that the worm revolves once every two minutes. The clock and telescope are driven by a series of weights on a cable and these are automatically wound up when necessary by an electric motor situated on one side of the lower half of the clock case. On the opposite side is a similar motor used for slow motion in right ascension which will be later described. Owing to the great ease with which the 45 tons weight rotated on the polar axis moves, a relatively small weight is required. About 400 lbs. of weight is sufficient, giving 200 lbs. tension on the winding cable, although about 50 per cent more is employed to take care of inaccurate balance.

QUICK AND SLOW MOTIONS

A great deal of thought was given to and time spent on the design of the mechanism for moving the telescope quickly to any desired position and accurately setting and guiding it during observing. It is evident that the efficiency of the instrument will greatly depend upon the quickness, ease and accuracy with which its motions may be governed. The great weight of the moving parts, 45 tons, required that the mechanism be both positive and smooth in action in order that, especially in the guiding motions, the telescope may respond immediately to the impulse of the operator, move smoothly to the desired position and stop positively and quickly.

The quick motions are operated by electric motors situated, for the right ascension in the hollow south pier head and for the declination in an auxiliary housing on the declination housing. It is evident that some method of connecting and disconnecting the axes with the motors is necessary as it is only when the position of the telescope is changed that this connection is required. When being driven by the clock or moved in slow motion, the axes must be free from the quick motion motors. Both motors are connected, by double worm reduction, reducing the speed from 1,100 revolutions to $\frac{1}{2}$ revolution per minute, to a differential gear box. The shaft on the other side of this differential carries a pinion meshing into the quick motion spur gear in the case of the declination axis, while for the polar axis the motion is transmitted by an auxiliary shaft and bevel gears. If the motors are running, the differential housings evidently revolve or idle without any tendency to turn the telescope. Similarly if the telescope is being moved by hand or driven by the clock or slow motions, the differentials also idle with no tendency to turn the motor shafts. Each of the differentials has a V-shaped groove on its periphery and a clamping band operated in right ascension by a hand wheel and in declination by an electro-magnet set in action by a push button switch. If either of these bands are clamped and the differential housing thus prevented from rotating, it is evident that the motion of the motor shaft will be transmitted through the differential gearing and turn the telescope. The speed in each co-ordinate is 45° per minute, sufficiently fast to turn from one position to another with little loss of time and yet slow enough so that no dangerous momentum is thereby generated.

The slow motions are also motor operated but on an entirely different principle in the two co-ordinates and must hence be separately described. They are designed to

give two speeds, a fast one for fine setting and a slow for guiding. The setting slow motion moves the telescope at the rate of 10 minutes of arc in 1 minute of time or one revolution in 36 hours. The guiding slow motion is one-twentieth of the setting speed or 30 secs. of arc in 1 minute of time or one revolution in 720 hrs. or 30 days. Although this last speed may seem excessively slow, it will not be found so if we consider the linear motion of the star image at the secondary focus. The equivalent focal length is 108 ft. and hence one second of arc is 0.0064 inches, 0.16 mm. hence the rate of motion is about three one-thousandths of an inch, eight one-hundredths of a millimetre in one second of time. The slit width of the spectrograph which will be the principal instrument used at the secondary focus, will be about two-thousandths of an inch and hence it is readily seen that with any faster speed it would be difficult to keep the star accurately centred on the slit.

The slow motions in declination are transmitted to the declination axis by means of a slow motion arm about 6 feet long of very rigid construction which can be clamped to a boss on the declination quick motion gear. The upper end of this arm, and with it the tube of the telescope when the clamp is engaged, is moved in either direction by a reversing motor. This motor moves, by worm reduction, through a two speed gear box of 20 to 1 ratio, a screw which engages in a nut on the upper end of the arm. The shift from the setting to the guiding speed is effected and can be actuated whether the motor is moving or stationary.

The slow motions in right ascension are actuated, without the intervention of a movable arm, by varying the speed of the driving worm and hence that of the telescope when the worm wheel is clamped to the polar axis. This variation in speed is effected by placing on the main driving shaft of the clock, the one that gears through an intermediate into the worm shaft, two differential gears, the left hand one for accelerating, the right for retarding. When the clock runs the differentials with their cases or housings run as units and the worm drives at the sidereal rate. If now the left hand differential case is stopped, the driving worm is accelerated in the ratio of one revolution in 30 revolutions of the worm. If this housing is released and the right hand differential case is stopped, the driving worm is retarded at the same rate. This gives the guiding slow motion speed. For the setting slow motion speed which is 20 times as fast as the guiding speed, the differential housings are rotated in the opposite direction to which the clock drives them, and at 20 times the speed, which accelerates or retards the worm 20 times as fast depending on which housing is rotated. This rotation is given by the slow motion motor, situated at the right hand side of the pendulum housing, which drives by worm reduction to ratchet tooth clutches on the differential housings. Normally the motor stands still and to stop either of the differential housings for the guiding motion, the corresponding clutch is engaged by a solenoid. Owing to the worm reduction the mechanism is irreversible and the throwing in of the clutches stops the differential and gives the guiding motion. To get the setting motion 20 times as fast, it is merely necessary to start the motor.

The method of clamping the worm wheel to the polar axis and the slow motion arm to the declination axis should now be described. On a hub on the lower side of the worm wheel a V-shaped groove is turned while on the quick motion gear are pivoted

four bronze shoes which fit and bear into this groove. Around these shoes are two semi-circular arms hinged at one end and drawn together at the other by a right and left hand screw which when drawn up tight forces the shoes into the groove on the worm wheel and hence causes the worm wheel to turn the quick motion gear (and hence the polar axis and telescope). A similar right and left hand screw clamps the slow motion arm in declination firmly in the V-groove in the hub of the declination quick motion gear and hence causes the tube to move with the arm. These screws are drawn up tight by means of half horse power motors working through worm reduction to a differential gear box on the clamping screw. The housing is prevented from rotating, thus driving the clamping screw home, by an adjustable spring clamp which will slip before unnecessary or injurious strain can be placed on the mechanism, and though the motor may not be stopped immediately the clamp is tightened, no damage will be done. The unclamping is positive as a ratchet action prevents the housing from rotating in the reverse direction and the motor is automatically stopped when the clamp is completely free by a switch cut-out.

A notable feature of all the mechanism for quick and slow motions and clamping on this telescope is that it is entirely enclosed and protected from dust. Further all the worm reductions and differentials are enclosed in dust proof housings filled with oil or grease, thus reducing the wear of the moving parts and reducing to a minimum the number of places requiring oiling and cleaning.

THE SETTING CIRCLES

My aim in the design and arrangement of the setting or finding circles was to effect a compromise between the easy reading and comparatively rough setting of the coarse painted circles and the troublesome reading though accurate setting of the finely divided silver circles; to combine, so far as might be, the advantages without the expense of both, and this, I believe, has been successfully accomplished.

As has been previously mentioned, the declination circle, contained within the declination housing, is 8 feet in diameter and graduated to single degrees. The graduation on this and all the other circles are relatively narrow, are cut to a considerable depth by the graduating tool and the grooves filled with white paint while the ground is painted black. The index mark is a groove of the same width also filled with white paint and coincidence can be readily seen and tenths of the graduation space estimated in any position of the telescope through a celluloid window in the declination housing. However, this circle is merely used to indicate the degrees, while subdivisions of degrees are obtained on an auxiliary circle, which is rotated by a pinion meshing into an internal gear on the rim of the declination circle. This secondary circle is subdivided into 5-minute spaces and single minutes can readily be estimated. A miniature electric lamp illuminates both circles simultaneously and the operator at one of the switchboards on the south pier can at a glance read the position in declination to a minute of arc and can also of course set the telescope as accurately as he can read.

In right ascension is a plain hour circle graduated to 5 minutes of time which serves to roughly indicate the hour angle of the telescope. The setting in right ascension is, however, made by means of the sidereal circle which is nearly nine feet in diameter,

graduated on the periphery to single minutes of time. This circle revolves around a boss on the upper side of the worm wheel and its friction in this bearing will evidently carry it around at the same rate as the worm wheel, although at the same time allowing it to be set to any desired position. It evidently will revolve at the sidereal rate, when the driving clock is going, and, if set to the sidereal time by a fixed index on the top of the clock case, will indicate sidereal time as long as the clock is kept going. Attached to the polar axis directly above the sidereal circle are four long index arms with index marks exactly adjacent to the graduations on the circle. These index marks are exactly 90 degrees apart and are respectively parallel and perpendicular to the declination axis. It is therefore at once evident that, after the circle has been once set at the beginning of observing, all that is necessary to find a star in right ascension is to turn the polar axis until one of the index arms points to the graduation corresponding to its right ascension. No mental arithmetic is therefore needed to compute the hour angle, as is necessary when an hour circle is employed for setting, and this method has the further advantage that the index position is not continually changing with the time as is the hour angle. Further, the graduations are close to the operator at the switchboard and can be accurately estimated to fifths and even tenths of a minute of time.

It will at once be seen that these setting circles enable settings to be made as accurately as necessary to find any object, indeed so accurately that flexure of the mechanical parts will probably induce greater errors. At the same time, they are read just as readily and easily as the ten-fold coarser graduations commonly used and have not the drawbacks and additional expense entailed by the finely graduated silver circles that were formerly employed.

THE BEARINGS

The main bearings on the declination and polar axes are evidently a very important part of the mechanism. The enormous masses to be moved, 45 tons on the bearings of the polar axis, are so great that unless the friction is reduced to the lowest possible limit, it will be difficult if not impossible to get smooth and regular action in the driving and slow motions and the efficiency of the telescope may be much diminished.

The practice hitherto universally employed, so far as I know, in the main bearings of equatorial telescopes, has been to employ plain cylindrical bearings and to relieve the friction on these bearings, which would be prohibitively great for smooth action in telescopes of even moderate size, by relieving devices of various kinds. These relieving devices have usually consisted in rollers forced up against the axes by levers, springs or weights and devised to carry about nine-tenths of the weight, thus materially reducing the friction. The latest relieving device has been that notably and successfully employed at the Mt. Wilson Solar Observatory on the polar axes of the 60-inch and 100-inch telescopes. This depends on the upward thrust, caused by the displacement of mercury in a trough attached to the pier heads, on enormous cylinders rotating with the polar axis. Although this is undoubtedly effectual and any desired proportion of the weight may be relieved by simply varying the depth of mercury in the close fitting trough, it is at the same time expensive, while the mercury is messy and disagreeable and hence to be avoided if possible.

I am of the impression that the reason cylindrical bearings have always been used is due to the idea that they were necessary to maintain the collimation of the axis and is a

logical development of the procedure used in the axes of transit instruments where carefully lapped cylindrical bearings rested in V's and the weight of telescope and axis was in some cases partly relieved by anti-friction rolls. I maintain, however, that there is by no means the same necessity for accurate collimation in the equatorial as in the meridian instrument and that even so the collimation maintained by the modern ball or roller bearing where the races are hardened and ground with the highest possible mechanical accuracy will be quite equal and probably superior to that given by a plain cylindrical bearing unless the latter has been most carefully lapped, a procedure which I am frank to say, I do not believe has been followed in equatorial telescopes.

I was hence determined from the first to employ ball or roller bearings only on the axes, for the purpose of simplifying the mechanism and reducing the friction. I found the Warner & Swasey Co.'s opinion entirely in agreement with mine and the only point to decide was whether to employ roller or ball bearings. The first preference was for the Timken bearing, a commercial product of high grade, widely employed in automobile bearings. This bearing uses conical rollers which, when opposed at the two ends of a shaft or axis, allow compensation for wear. This, however, is of no particular moment in a telescope where the motions are so small that the wear is reduced to a negligible quantity. These bearings are not self-aligning so would have had to be mounted in a spherical seat, but this again is not of great moment. The difficulty was that the Timken Co. did not regularly make bearings of a large enough size and were not willing to make them specially. It was highly desirable that the bearings be made by a firm accustomed to this work and the S.K.F. self-aligning ball bearings (manufactured in Sweden) were finally selected.

Regular commercial sizes of this bearing were available for the polar axis and the outer declination axis bearing but special bearings had to be made for the inner declination radial, the double thrust for the declination and the bearings for the worm wheel. These bearings are beautifully made, have a mirror-like finish on the bearing sleeves, and are evidently extremely accurate. They are of the self-aligning type and will work just as freely and smoothly whether the shaft and journal are true and correctly lined up or not. This feature is obtained by grinding the bearing surfaces spherical, the centre of the sphere being the geometrical centre of the bearing. Hence the inner sleeve of the bearing can be rotated at any angle with the outer sleeve and as the balls are held in cages, everything remains intact and secure. A good idea of the form of the bearing is given in Fig. 14 where the inner sleeve is shown rotated through 90° and in Fig. 2 where the bearings are seen in place on the end of the polar axis.

On the upper end of the polar axis the bearing is 8.740 inches bore, 18.26 inches outside diameter and 5.25 inches thick with balls 3 inches diameter. The lower radial bearing dimensions are 9.025 inches, 19.31 inches, 5.25 inches, with balls $3\frac{1}{8}$ inches diameter, slightly larger than the upper as it has a greater weight to carry. The thrust is taken by a S.K.F. regular ball thrust bearing resting on a rocker. This rocker has a cylindrical surface on top and bottom, the axes of the two cylinders being perpendicular to one another, so that even if the end of the polar axis were not true or normal to its axis of rotation, this rocker would allow the bearing to properly seat itself in any position.

On the outward end of the declination axis, the bearing is of the same dimensions as that at the lower end of the polar axis but owing to the large diameter of the axis near the tube the bearings had to be specially made. Both the radial and the double thrust bearing are mounted in a self-contained sleeve which bolts to one side of the cubical centre piece of the polar axis. The radial bearing is 16 inches bore, 21 inches outside diameter, 3 inches thick with two rows of balls $1\frac{1}{4}$ inches diameter. The double thrust ball bearing rests in spherical seats in order to be self-aligning as the others and is $15\frac{7}{8}$ inches bore, $20\frac{7}{8}$ inches outside diameter and $5\frac{1}{4}$ inches thick.

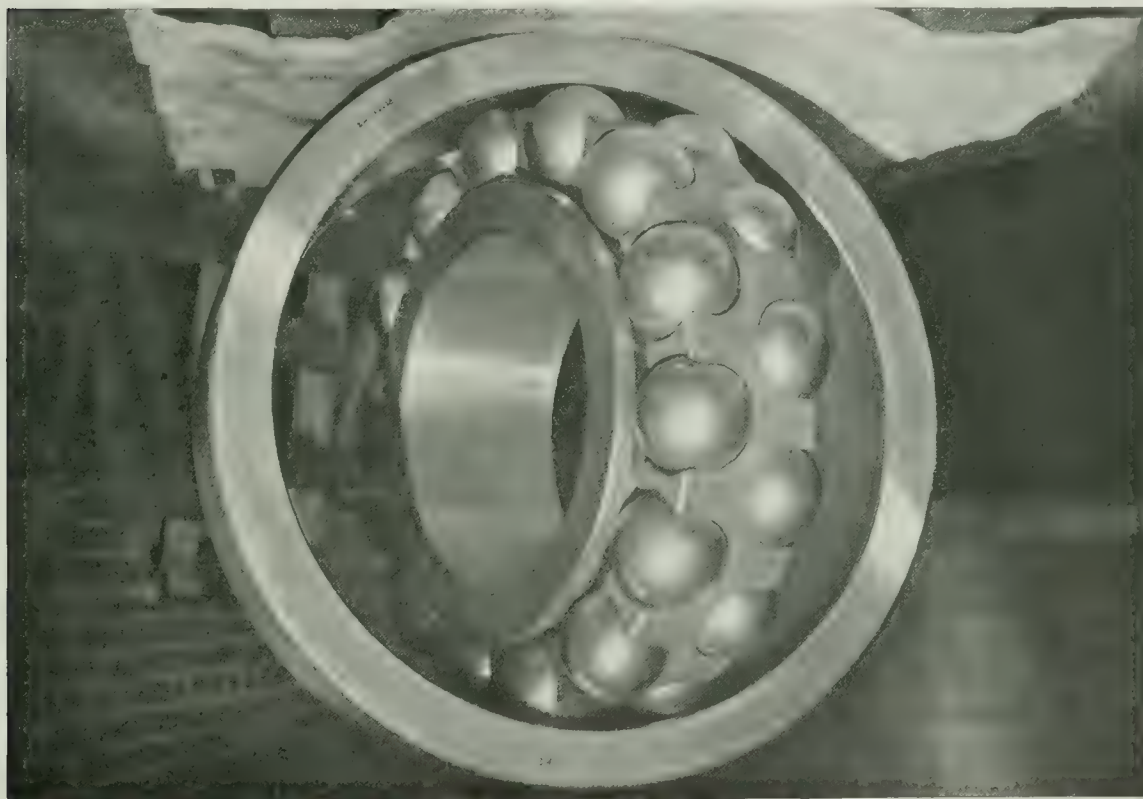


Fig. 14. Ball Bearing for Polar Axis.

The ball bearings of the worm wheel have $1\frac{1}{2}$ -inch balls and are 16 inches bore, 22 inches diameter and $2\frac{1}{2}$ inches wide while the thrust bearing dimensions are 18 inches 23 inches and $2\frac{1}{2}$ inches.

All these ball bearings have a rated capacity between 5 and 10 times the load they have to carry at a speed some hundred times as great as they will be used at. They are all enclosed in dustproof housings filled with light grease and will evidently operate for an indefinite time without attention.

The frictional coefficient is remarkably small due doubtless to the mechanical perfection of the bearing surfaces. Some experiments have been carried out with the finished telescope in an attempt to determine the force required to turn it on its bearings, but the actual frictional drag in the ball bearings cannot be determined as there are other

factors entering. If we take the polar axis for example and attempt to revolve it on its bearings, we have to turn it against the friction in the ball and ball thrust bearings at the ends of the axis, the friction of the worm wheel in its bearings, the drag of the clamping mechanism in right ascension which cannot be entirely removed even when completely unclamped, and finally and most important, the friction in the quick motion differential gearing, its connecting shafts, and in the differential housing clamp. However, the friction in the differential mechanism can be differentiated from the rest by taking off the quick motion pinion, when there will remain only the first three frictional drags.

The tube was set at declination 0° , at right angles to the polar axis, and turned down below the axis until horizontal. A string was attached to the upper end of the tube running over a pulley so placed that the pull was tangential to motion around the polar axis. Weights were then placed on the string until it started to move and were found to be :—

With all mechanism attached.....9 lbs.

With differential mechanism detached.....3.25 lbs.

The distance from the axis to the point of attachment is 26 feet. As the friction of the worm wheel on its bearings is 2 pounds at 4.5 feet, this will leave 2.9 pounds for the friction on the bearings of the polar axis plus the drag of the right ascension clamp. Probably, therefore, the bearings alone would not require more than 2 pounds pressure at a radius of 26 feet to set the mass of 45 tons in motion, a striking confirmation of the mechanical perfection of the bearings, not only as regards absence of friction but also in respect to maintenance of collimation, for if the bearing surfaces were not almost truly spherical, the friction would undoubtedly be much larger. It seems to me also undeniable proof of the superiority of well made ball bearings alone for the axes of equatorial telescopes over the combination of cylindrical bearings and any kind of relieving system. I have no data as to the friction in bearings relieved by mercury flotation but doubt whether it can be made as small as that given by these ball bearings.

The force required to move the tube in declination is somewhat greater than in right ascension, undoubtedly owing to the greater drag of the heavy slow motion arm in its clamping groove. But even at the lower end of the tube the telescope can be readily moved by hand to any desired position when unclamped and its great freedom of movement will be a great advantage in operation, as well as contributing markedly to the smoothness and certainty of operation of the slow motion mechanism.

ELECTRICAL EQUIPMENT

A great deal of the success of the mounting and of its efficiency in operation depends upon the care used in the design and installation of the electrical equipment. Practically all the operations of setting, clamping and guiding are performed electrically. There are seven electric motors in the mounting of the telescope besides several magnets, solenoids and interlocking switches and mechanism and there is necessarily a rather intricate system of wiring and connections, which, unless carefully designed and thoroughly constructed and installed, would be bound to give trouble. One of the weak points of some telescope mountings has been the slipshod way in which the wiring has been done and the faulty means employed to transfer connections to the moving parts. It was

very necessary in this mounting, where some 90 odd wires were required to enter the polar axis from the main switchboard for the various operations, that the wiring be done in a thoroughly mechanical and permanent manner, and that the connections to the parts between which there was relative motion should be made in a way to prevent future trouble. The usual means employed for this latter purpose had been insulated rings with sliding contacts, but owing to the great number of such connections that would be required and the very large diameters of the shafts on which they would have to be placed with the practical certainty of faulty connection sooner or later, it was decided to avoid these if possible. The greatest angular rotation of either polar or declination axis is not much greater than 180 degrees in this mounting and it seemed that a flexible permanent connection between the wires coming down the polar axis and those going along the declination axis would serve the purpose. Some 96 wires come from the main switchboard situated at the north side of the north pier and go in a pair of conduits to the upper end of the polar axis where they are loosely bundled and taped together, enter a hole in the bearing cap and axis 2 inches in diameter and pass down the hollow upper section of the polar axis to the declination axis. Here they divide, part of them going to the outboard end of the declination axis in conduit through the hollow declination bush, where they serve to operate quick and slow motion motors, clamps, etc., in declination, and part of them going through a hole in the declination axis into the centre piece of the tube, where they are led through flexible armoured conduit to terminal boxes at the upper and lower ends of the tube and serve to make the connections to the slow motion operating switches, the spectrograph and illumination. The rotation of the polar axis produces torsion in the bundle of wires passing down it but as this torsion is only over 180° in a distance of 10 feet, it will evidently not have appreciable action on the permanency of the connection. Similarly, the wires that pass through the declination axis into the tube will also be subject to bending as the declination axis rotates. Injurious effect on these wires by the rotation of about 180° is avoided by coiling them loosely around the declination axis about one and a half times before they enter the hole. Rotation of the declination axis therefore simply winds and unwinds this turn and introduces no abrupt bend in the wires but only a very gradual change in curvature as the axis rotates. No sliding contacts whatever are used, and I am confident that the connections will give no trouble for an indefinite period. The most likely place where trouble would occur is in the wires passing through the hole in the declination axis to the tube. However, they end in a terminal board on the flanged end of the axis and if any of them break by the winding and unwinding there will only be the length of 3 or 4 feet between this board and their connection to the bundle coming down the polar axis that would need replacing.

It was at once seen when the required operations came to be considered, that continuous current would have to be used, for not only are direct current motors more easily started and reversed than alternating but they have more initial torque and are in every way more suitable. Further, direct current would be required in any case for operating the magnets and solenoids so a motor generating set of 10 kilowatts capacity supplying direct current at 220 volts was installed on the ground floor of the observatory. The motor side is a 220 volt 3-phase 60 cycle motor supplied by current from the B. C. Electric Railway Co

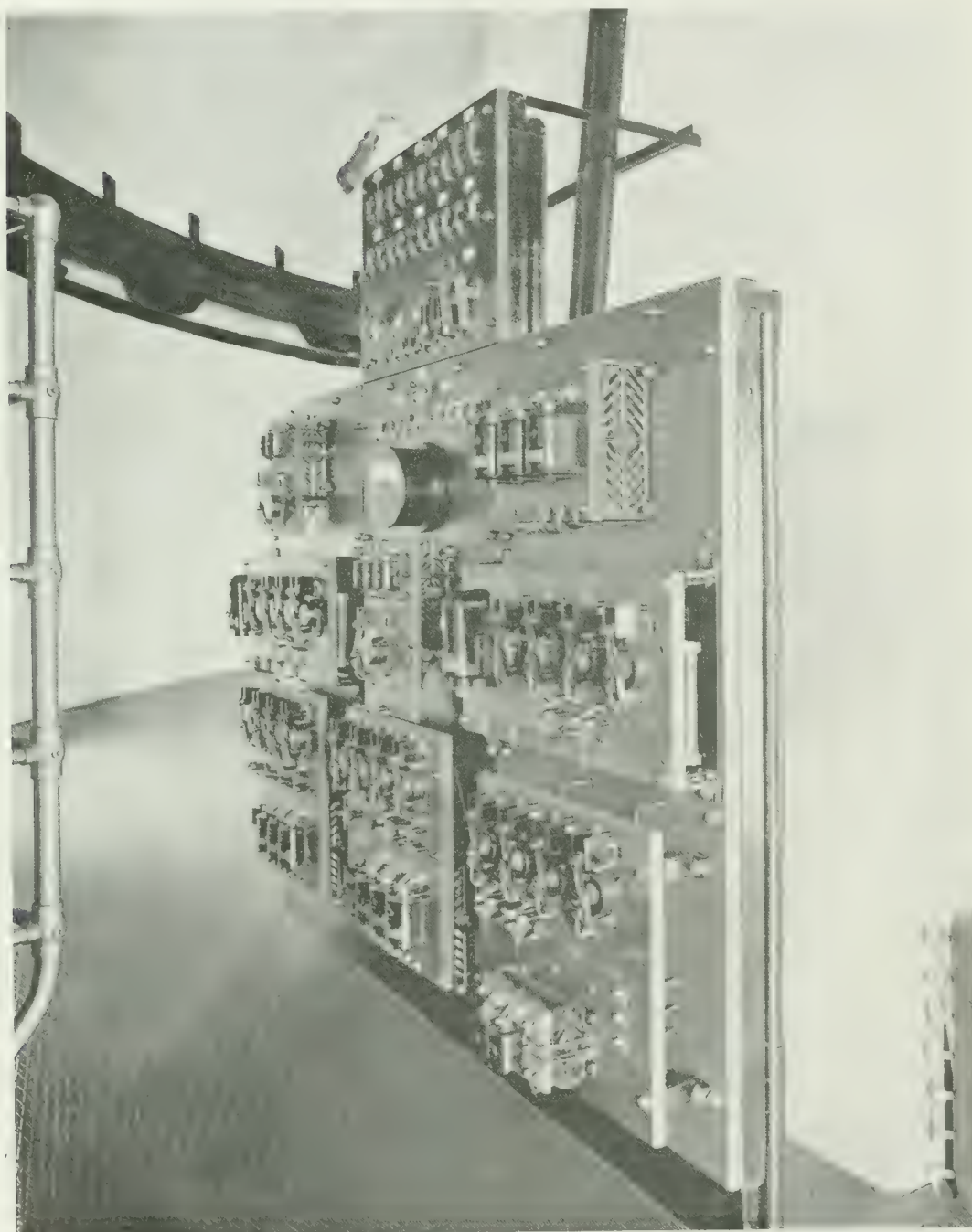


Fig. 15. Main Switch Board—North of North Pier.

The distribution and operation are controlled from five switchboards :—the main control board on the north side of the north pier, two auxiliary operating boards connected in multiple and duplicates of each other on the east and west sides of the south pier, and two small portable observing boards one each at the upper and lower ends of the tube.

The main control board has three slate panels and is about 9 feet wide and 6 feet high and the general appearance is well shown in Figure 15. As the motors are required to be started and reversed instantaneously and without using any hand rheostat, automatic electric controls for each motor are installed on this switchboard. By simply pushing a button or moving an operating handle to left or right on the operating boards the motors may be started in either direction or instantaneously reversed, resistance in the armature circuit being automatically cut out as the speed increases. On this board also are fuses and switches for each circuit, a direct current ammeter, and a reduction transformer from 110 to 6 volts for the illuminating lamps.

The operating boards on the east and west sides of the south pier are so placed that the setting circles can be conveniently read from them and are intended for the approximate setting of the telescope to the catalogue position of the star. In the operation of the telescope, although it would be easily possible for one person to manage it, some time will be saved by having the observing assistant make the approximate setting from these switchboards and the observer at the finder, the fine setting by the portable switchboards. The arrangement of the switches on these operating boards, which are duplicates of each other, are shown in the general photographs of the telescope. The three operating handles are, from north to south: R. A. quick motion motor, Dec. quick motion motor, dome revolving motor. The push button switches similarly are from north to south: R.A. slow motion clamp, Dec. slow motion clamp, Dec. quick motion clamp, R.A. Illumination, Dec. Illumination. The two plugs at the lower part of the board are for hand lamps for general illumination. Hence the assistant, at the one of these boards from which the declination setting circles can be most easily read, can simultaneously, if desired, turn the telescope in R.A. and Dec. to the desired positions and revolve the dome to suit. As soon as set, he unclamps the quick motions and by pushing the respective switches, clamps the telescope in the slow motions. Interlocking automatic switches form safety arrangements, which prevent the slow motion clamps being engaged while the quick motions are clamped, or, vice versa, prevent the quick motions being engaged while the telescope is clamped in slow motion.

The portable fine setting and guiding boards at the upper and lower ends of the tube are light aluminium boxes with a series of push button switches arranged on them as shown in the photograph of the upper end of the tube, Fig. 12. The board for the upper end of the tube has in addition to the slow motion switches, clamping switches in R.A. and Dec. These are intended for the observer to throw in the clamps as soon as the telescope is accurately set. At the upper end of the tube, it can be readily moved by hand to the desired position and at once clamped. At the lower end, however, owing to the shorter leverage, the telescope cannot be so readily moved by hand, the assistant can be readily told when to clamp, and clamps on the portable board are not necessary. The arrangement of the fine setting and guiding switches is clearly shown on the photograph, Fig. 12. The upper buttons in either R.A. or Dec. actuate the slow guiding

motion in either direction, while when this button is held down and the lower button pressed, the fine setting motion, 20 times as fast as the guiding motion is actuated. With the fine setting motion, the observer can readily and rapidly centre the telescope on the object while the guiding is sufficiently slow and delicate to enable accurate guiding to be obtained. If the object moves too slowly with the fine guiding a simple pressure on the lower button rapidly accelerates it. The slow motions operate most satisfactorily, the telescope responding instantaneously and smoothly and without apparent backlash, to the operating switches. The similar arrangement of the two slow motions and the identical speeds in the two co-ordinates are a distinct advantage and I can not see how the arrangement and operation could be improved.

The illuminating lamps for the R.A. and Dec. setting circles are operated from the boards on the south pier while the lamps for the guiding microscopes on the double slide plate holder and the ocular on the long focus finder are actuated by small switches adjacent to them. The intensity of the guiding illumination can be made as desired by an adjustable rheostat.

THE FINDERS

Three finders are provided, one long focus 7 inches aperture and 30 feet focus situated 180° from the place of attachment of the declination axis, and two short focus finders each of 4 inches aperture and 60 inches focus situated 90° on either side of the long focus finder. The short focus finders are of the usual type with coarse cross wires that can be seen against the sky background without illumination. The long focus finder is tubeless, the objective being attached to a bracket near the upper end of the tube and the ocular in a short length of tube adjustable laterally to enable it to be collimated parallel to the main optical system. This ocular is provided with illuminated cross wires of fine wire and was intended for getting stars centred on the slit of the spectrograph. The whole surface of the slit jaws only subtend slightly more than a minute of arc at the Cassegrain focus and it was thought stars might be troublesome to pick up if only centred by the ordinary finder. However, experience has shown that careful setting with the 4-inch finder is sufficient and the long focus finder is not necessary in setting on the slit.

OCULARS

A very complete set of high grade three-lensed oculars for visual observations was supplied by the Brashear Co. with focal lengths ranging from $\frac{1}{4}$ inch to 4 inches. From $\frac{1}{4}$ -inch to 1-inch focus the oculars are as usual mounted in $1\frac{1}{4}$ -inch tubing but the $1\frac{1}{2}$ -inch, $2\frac{1}{2}$ -inch and 4-inch oculars have 2-inch field lenses mounted in $2\frac{1}{2}$ -inch tubing and cover a wide field.

For observing at the principal focus at the centre of the upper end of the tube, an auxiliary system is provided consisting of a right angled prism of sides $1\frac{1}{4}$ inches square mounted in an adapter attached to the double slide plate holder in place of the regular plate holder. This prism is some 2 inches above the focus and reflects the pencil from the principal mirror at right angles towards the side of the tube. Mounted on the same adapter with its axis along the axis of this reflected pencil is a symmetrical triplet designed by Hastings of $2\frac{1}{2}$ inches aperture and 11 inches focus. The conjugate focus of this lens

corresponding to the principal focus of the mirror is situated at the edge of the tube where it can be observed by an ocular held in an adjustable adapter attached to the flanged circular plate at the upper end of the periphery of the tube.

When the Newtonian mirror is used another adapter holds the ocular directly in the double slide plate holder. When the Cassegrain attachment is used, with the spectrograph not attached, a simple casting which carries a focusing tube for holding the ocular bridges the hole in the centre of the cell and observations can be made directly. If, however, the spectrograph is in place a tube containing a right angled prism and triplet objective similar to those used at prime focus with place for ocular at the outer end is attached to the spectrograph frame above the slit by a bayonet joint and can be inserted or removed instantly. All that is required, if visual observations are desired when the spectrograph is in place, is to insert this tube, which intercepts the pencil from the secondary about 8 inches above the focus, and focus. This is a great advantage if visitors desire to see any object when the spectrograph is being used as this tube can be attached in a moment without interfering with the spectrograph or any other adjustments, and it can be detached as quickly and the spectrograph brought back into use.

THE DOUBLE SLIDE PLATE HOLDER

This attachment for making direct photographs at the principal or Newtonian focus is a beautifully designed and constructed piece of mechanism. The size of plate used is 4 inches square which subtends an angle of nearly 40 minutes of arc square, quite large enough to cover the whole field of good definition. The plate holders, of which there are two, are made of steel with hardened steel bevelled guides which are clamped against corresponding hardened stops on the carrier so that the plate holder may be removed when desired for refocussing and put back exactly to the same position. Adapters for holding knife edges, whose plane is in precisely the same plane as the plate in the plate holder, for focussing either at the principal or Newtonian foci, are provided with similar guides to insert in place of the plate holder. So also are adapters for holding the prism and objective system for the principal focus and the oculars for the Newtonian focus previously described. The carrier for the plate holder is movable by a double slide mechanism quite similar to that of plate holders previously described but as this is to be used at the principal focus, means must be provided for transmitting the motion from the side of the tube to the two slides at right angles to each other. As it would not do to have the two rods and handles for rotating the slide screws 90° apart, as it would be impossible to reach both, a rod and concentric tube each with wooden handle reach from the side of the tube to one of the slide screws. This screw is turned by the central rod while the outer tube turns a concentric sleeve on this screw which is geared by bevel gears and flexible connecting shaft to the other slide screw. Hence both slides can be moved from the one position at the side of the tube. When the plate holder is at the Newtonian focus a similar very short rod and tube is attached and both slides can be moved from the one place as before. This mechanism is well shown in the figure, Fig. 16, and works admirably.

The guiding microscopes, of which there are two, one on each side of the plate holder also require special appliances to adjust them over suitable guiding stars when

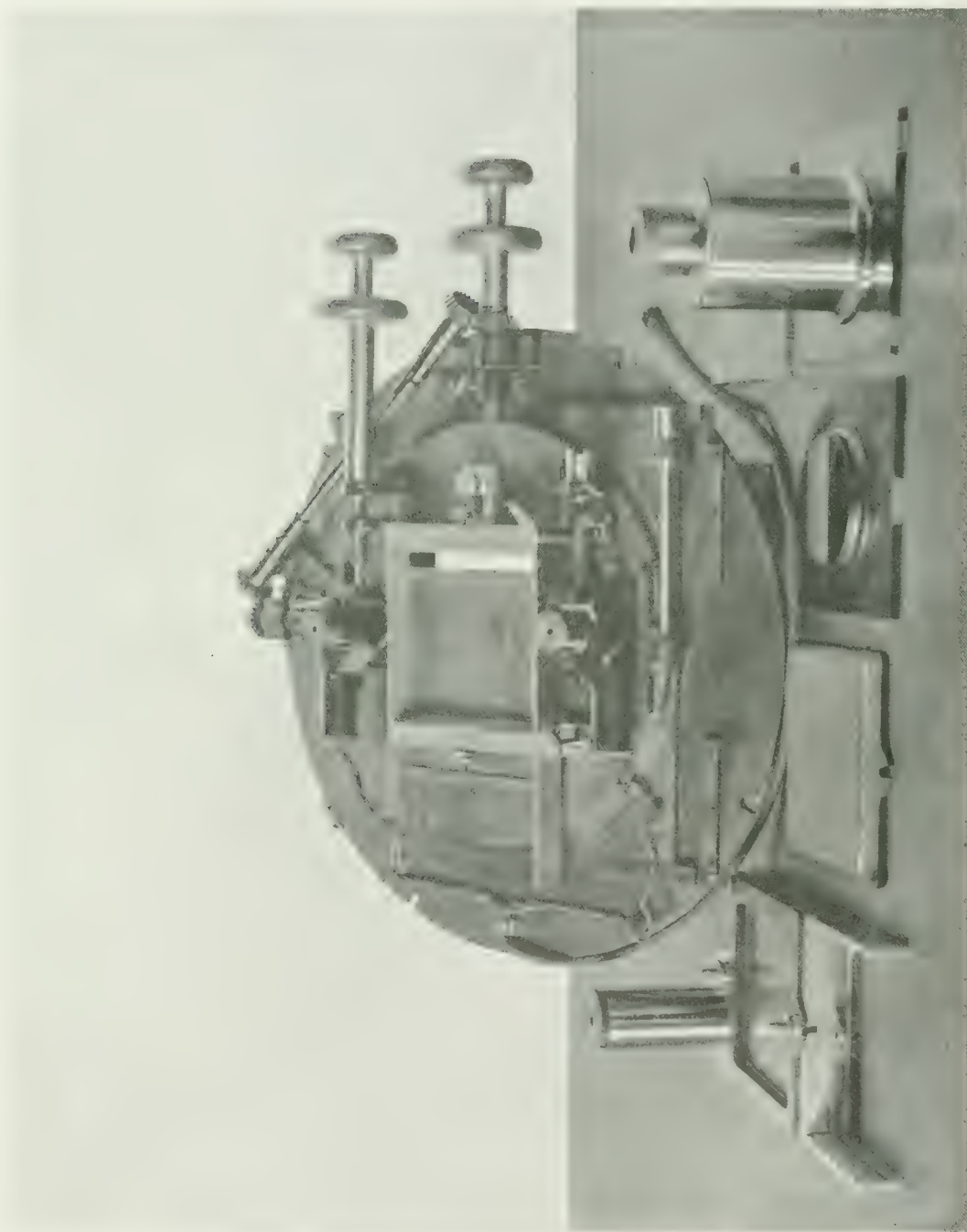


Fig. 16. Double Slide Plate Holder.

the plate holder is used at the principal focus. When used at the Newtonian only, such appliances would not be necessary and they could be adjusted by hand while the illuminated cross wires and image can be viewed by simple oculars as in the ordinary double slide plate holder. When the plate holder is at the centre of the tube, however, one can neither reach over to move the ocular nor to see when it is over a suitable star. Similar right angled prisms and triplet objectives, though of course much smaller, are used for carrying the light to the side of the tube where it is viewed by oculars held in other parts of the same adjustable adapter that carries the main observing ocular previously referred to and which also holds the extension rod and handles for moving the slides. The frames which carry the cross wires, illuminating systems and prism objective systems for each of the guiding microscopes, move also on two slides at right angles to each other, the longitudinal one being moved rapidly by a triple screw while the transverse motion is effected by a pinion concentric with the screw gearing into a rack on the slide. The same rod and tube that moves the main slides is also interchangeable with the two microscope frames and as they can be rapidly moved over a considerable range both longitudinally and laterally at each side of the plate, suitable guiding stars, which can be observed through the oculars adjacent to the handles, can be readily picked up. The use of two microscopes is for the purpose of guarding against rotation of the field which may be caused by differential refraction or imperfect adjustment of the polar axis and this can be corrected by rotating the upper part of the slide carrying plate holder and microscopes by a tangent screw also operated by a similar handle.

In case of any unforeseen, unavoidable motion of the telescope or one uncorrectable by the slides, which would produce wings on the brighter stars, the holder is fitted with a spring-flap shutter which instantaneously closes and shuts off the light from the plate by releasing a catch.

Focussing is done at the principal focus by moving the central tube which carries the plate holder by a focussing ring as previously described. At the Newtonian focus the plate holder is attached to a flanged tube which can be slid in and out of the adapter attached to the side of the telescope tube to the approximate position. The final focussing and placing of the plate perpendicular to the optical axis is effected by three micrometer screws on the flange.

The position of focus is determined by the knife edge test, a knife edge being provided accurately placed in the same plane as the sensitive film and the illuminated mirror surface can be viewed directly by the eye at the Newtonian focus, and through the intervention of prism and lens system with the ocular removed at the side of the tube when the plate holder is in the principal focus.

The whole plate holder was very carefully thought out and is beautifully made so that it works with the greatest ease, smoothness and precision.

THE SILVERING CAR

Although this is perhaps not strictly an accessory of the telescope it is as essential for its successful operation as any other part of it. Owing to the great weight of the mirror and cell, about 6 tons, and to the necessity of removing them together for resilvering the surface of the former, it is evident that some thoroughly safe and easy way of removing

and attaching this heavy and awkward piece and of rocking it in some way to flow the solution evenly over the surface must be devised, and what is called the silvering car, which can be seen more or less fully in Figures 3, 4, 5, is the successful result of the efforts of the Warner & Swasey Co.

For removing the mirror and cell, the telescope tube is placed in the vertical position on the east side of the polar axis and the car which is a massive rectangular structure, running on 4 pairs of wheels of 8 feet gauge, and built of structural steel, is run directly under the mirror cell on two tracks 8 feet apart of cast steel bars, $\frac{1}{16}$ inch thicker than the steel plate floor, which are laid on two of the girders directly under them. One each of the pairs of wheels are flanged, the flange running in a half-inch space between the steel bar and the plate floor. The tracks run due east from the telescope pier to the east wall of the dome and are exactly centrally situated north and south. As the flanges keep the wheels aligned on the tracks, the car can be moved only east and west along a diameter of the dome and will hence come vertically under the tube when placed on the meridian and at Dec. $48^{\circ} 31' N$.

On the heavy girders forming the base of the car to which the wheels are attached, a massive casting consisting of a hollow cylindrical centre section with flanges at top and bottom is bolted and thoroughly braced by angles at the top. This cylinder which is bored to a diameter of 12 inches and is about 3 ft. high, is vertical and moving up and down in it is a plunger actuated by a screw. This screw can be turned by geared-down hand wheels or by an electric motor so as to move the plunger in the cylinder up and down over a range of two feet. As some 840 turns of the hand wheel are required for this movement it is evident that the motor will be a very useful accessory leaving only the final two or three turns for the hand wheels.

This plunger is conical at the upper extremity ending in a hemi-spherical cavity in which is placed a two-inch steel ball.

Resting on this ball is a three-armed rocker built up of steel castings, the arms being nearly 4 feet long and carrying projections on their ends which will fit on the outer edge of the mirror cell. The ball support is situated some eight or ten inches above the plane of the supporting blocks on the three arms so that the rocker, cell and mirror will be supported at the centre of gravity of all three and a comparatively slight effort is required to move the rocker on the plunger there being a freedom of motion of about 10 degrees all around.

When this rocker is brought centrally under the mirror cell, the plunger is elevated until the rocker arms are bearing firmly on the cell. Before removing the bolts which fasten the cell to the central section of the tube, it is necessary to prevent the rotation of the tube on the declination axis and the polar axis on its bearings which would inevitably result in great damage unless the unbalanced weight caused by the removal of six tons from the end of the tube was supported in some way. Consequently, the outer end of the declination axis is supported by a vertical steel box girder which is counterpoised and moves vertically in an outer telescoping girder which extends between the steel observing floor and the ground floor of the building a distance of 21 feet. A small trap door in the steel floor allows this girder to be easily run up on its guiding rollers until a conical point on the top enters a corresponding socket in the declination housing. The

girder is seen in position in Fig. 4. A hole in the proper position through this girder enables a short piece of I beam resting on the floor to be pushed through and this holds up the outer end of the declination axis and prevents rotation on the polar axis. As the tube is vertical and in equilibrium, though unstable, it can be easily prevented from turning by lashing the upper end to rings in the main ribs of the dome provided for this purpose.

The cell can now be safely unbolted, the plunger lowered as far as desired, see Fig. 5, and the car moved to the east on its tracks until well out of the way of the tube. A light steel platform of suitable height for working at the mirror with a railing around it is built concentric with the cell, and from this platform the operations required in silvering can be readily performed. A band of paraffined paper about 8 inches high securely tied around the periphery and a tight fitting central plug for the hole make the mirror into a dish to hold the solutions while the rocker enables them to be moved uniformly and regularly over the surface. Pulling out the central plug allows the solutions to drain away into any receptacle and the silvering can hence be easily performed.

After being silvered, the mirror and cell can be as readily attached by the reverse operation.

The silvering car also serves to remove and replace the spectrograph on the tube but this operation will be described under the spectrograph.

CHAPTER VII.—DESCRIPTION OF THE SPECTROGRAPH

GENERAL

Although in one sense not an accessory of the telescope, indeed the telescope may more properly be called an accessory of the spectrograph as its only function is to increase the quantity of star light incident upon the spectrograph slit, yet in another sense, in that it will be practically permanently attached to the telescope and can not be used without it, it may be called accessory and as such should be described along with the telescope.

Most of the early stellar spectrographs attached to telescopes were of the universal type as they could be adapted to use in various forms, with different dispersions, and at different regions of the spectrum. These adjustable instruments were probably selected in the beginning as observing methods had not become standardized and it was felt that a choice of different dispersions and regions would prove useful in general experimental research. Good examples of these types were the spectroscopes supplied by the Brashear Co. to the Allegheny, Yerkes, Ottawa and other observatories which, though undoubtedly fine examples of the instrument makers art and well adapted for general use, were unsuitable for the particular line of work—the determination of stellar radial velocities—into which stellar spectroscopy was soon narrowed. It was soon found that only one limited region of the spectrum was used and at first only one dispersion and that the adjustable features were not needed and were indeed a source of weakness in rendering the spectroscope more subject to differential flexure, causing relative displacements of star and comparison lines, thus introducing errors into the results.

Consequently the universal form of spectroscope was abandoned for radial velocity work, and a rigid fixed form developed such as the Mills Spectrograph of the Lick Observatory, the Bruce of Yerkes and the Hartmann of Potsdam. These were all satisfactory instruments and very accurate observations were obtained by them. They had the drawback, however, that the spectrograph proper and the truss which attached it to the telescope tube were one and the same construction and the flexure, just as in a beam supported at one end, was a maximum. A great improvement in design was introduced by Campbell and Wright at the Lick Observatory who made the spectrograph proper self-contained and attached it to the telescope by an external supporting truss frame in which the spectrograph was held flexibly at two suitably chosen supporting points. The flexure in such a case was evidently only a fourth or less of that of the earlier type and this form has been adopted in all recent spectrographs, including the Ottawa single prism where flexure in the extended form of a one prism instrument was reduced to a minimum by adding a third suitably automatically counter-balanced support system.

In the spectrograph for the 72-inch reflector, I have attempted to combine the advantages of the self-contained spectrograph box carried in an attaching frame by a two point flexible support system, with the flexibility and general usefulness of a universal instrument.

In more recent years the narrow field of radial velocity observation of the stars in the spectral region around $H\gamma$ with a three prism spectrograph of linear dispersion about 10 Å per millimetre has been broadened to include observations with one and two prisms, with various lengths of camera and at various regions of the spectrum. No single spectrograph, indeed no two or three spectrographs, would be likely to meet the varied demands in spectroscopic investigation that might arise with such a powerful instrument as the 72-inch reflector. Hence, owing to the expense that would have to be incurred for such a battery of spectrographs, it seemed wise to try and devise a universal type of instrument, in which the change from one type to another could be made as quickly as or even more quickly than spectrographs could be changed on the telescope, while at the same time any desired or used adjustment could be rapidly and certainly re-obtained. At the same time the spectrograph must be as rigid and as little subject to flexure as any of the fixed form types.

This purpose has been, I am convinced, accomplished and the methods employed will be developed as the description proceeds. The optical parts of the spectrograph were made by the Brashear Co. and the mechanical parts by the Warner & Swasey Co. The material, size and form of the optical parts were determined by the writer and the principles and general form of the mounting with the details of the minimum deviation link work, slit head, comparison and guiding apparatus, constant temperature arrangements, etc., were given to the Warner & Swasey Co. The latter are, however, responsible for working out the mechanical construction, the form and material of the spectrograph box and attaching frame and the general details and style of construction and finish of the instrument. I need say no more in commendation of their work than to state that it is quite in keeping both in harmony of design and character of workmanship, with the work on the telescope mounting.

THE OPTICAL PARTS

I was influenced in determining the effective aperture of the spectrograph, the material of the prisms and the form of collimator and camera lenses chiefly by my own experience and experiments with spectrographs, but Adams' successful use of prisms of $2\frac{1}{2}$ inches, 63 mm., effective aperture showed the possibility of obtaining good prisms as large as this and influenced me in the decision to use a large aperture.

Practically all spectroscopists are agreed as to the advantage of a long collimator and the only drawback hitherto has been the uncertainty of obtaining suitable large prisms. I had used successfully a prism of 2-inches aperture in the Ottawa single prism and Adams prisms of $2\frac{1}{2}$ inches aperture at Mt. Wilson. Hence it was decided to use prisms of $2\frac{1}{2}$ inches aperture for this spectrograph and as the ratio of aperture to focal length in the Cassegrain is 1 to 18, this would make the collimator of 45 inches focal length.

The most suitable material for the prisms was the subject of considerable thought, experiment and calculation. As I have previously said,¹ I have long been of the idea that the O 102 dense flint used in most spectrographs is too dense and absorbing and some experiments of mine recorded in the same publication show marked advantages for a light baryta flint prism over the O 102 glass. The measurements of the absorption of various glasses of the Jena Co. were obtained and compared and calculations were made of the absorption and reflection of prisms of $2\frac{1}{2}$ inches aperture of different materials. Using these calculations they were reduced to similar conditions in regard to dispersion and the relative efficiency of spectrographs with prisms of these materials was computed. These data are given in the accompanying table (Table VII) and unmistakably indicate the superiority of O 118—ordinary flint—of the Jena Works. These conclusions as to its superiority were confirmed by Selesinger's measures of the absorption of the flint element of the 30-inch Allegheny objective, made of this material which came out remarkably low. Moreover, this glass is made in large quantities and is much more likely to be homogeneous than some of the less used types. Consequently, I had no hesitation in choosing it for the prisms of the spectrograph.

Material for the three prisms was ordered from the Jena Co. by the Brashear Co. in August 1914 but owing to the war was not obtainable. But that the choice of material was a wise one has been proved by the use of a 60° prism of $2\frac{1}{2}$ inches aperture made of the same material by the Hilger Co. for a Littrow Spectrograph for Toronto University, which has kindly been temporarily loaned to me by Prof. Chant. Experimental work with this prism shows it to be remarkably transparent in the violet considering its density and dispersive power. Although its dispersion is only some 20 per cent less than the O 102 glass, its absorption at $\lambda 4000$ is certainly less than half the denser glass.

¹ Pub. Dom. Obs'y., Ottawa, I. p. 188.

TABLE VII—TABLE OF TRANSMISSION, DISPERSING AND RESOLVING POWER

(Prisms of 63 mm. aperture of various glasses)

Material Jena Numbers	Number of Prisms	Devia- tion at λ 4200	Angle of Prisms	Trans- mission of Prisms	Angular Dis- persion at $H\gamma$	Linear Dispersion A per mm. at $H\gamma$ Cameras of Focal Lengths			Resolv- ing Power at λ 4200
						381 mm.	711 mm.	965 mm.	
U.V. 3248	1	48 31	65 45	.822	5.24	103.3	55.3	40.8	16,160
Ultra-violet flint.....	2	97 02		.703	10.84	51.6	27.7	20.4	32,320
	3	145 33		.615	15.72	34.4	18.4	13.6	48,480
	4	194 04		.556	20.96	25.8	13.8	10.2	64,640
O 722	1	51 41	64 15	.657	5.90	91.8	49.2	36.2	18,260
Baryta light flint.....	2	103 22		.451	11.80	45.9	24.6	18.1	36,520
	3	155 03		.321	17.70	30.6	16.4	12.1	54,780
O 578	1	52 07	64 0	.636	7.12	76.0	40.7	30.0	22,000
Baryta flint	2	104 14		.422	14.24	38.0	20.4	15.0	44,000
	3	156 21		.291	21.36	25.3	13.6	10.0	66,000
O 118	1	50 00	60 0	.768	8.51	63.6	34.1	25.1	
Ordinary flint.....	1	54 40	63 0	.756	9.86	54.9	29.4	21.7	30,450
	2	109 30		.603	19.72	27.4	14.7	10.8	60,900
	3	164 00		.503	29.58	18.3	9.8	7.2	91,350
O 102	1	60 00	64 0	.467	12.89	42.0	22.5	16.6	52,700
Dense flint	2	120 00		.235	25.78	21.0	11.2	8.3	105,400
	3	180 00		.126	38.67	14.0	7.5	5.5	158,100

The dimensions of the three prisms were to be as follows:—

1st prism sides 4.83 in., 122.9 mm.; Base 5.05 in., 128.2 mm.

2nd prism sides 5.07 in., 129.1 mm.; Base 5.30 in., 134.6 mm.

3rd prism sides 5.31 in., 135.3 mm.; Base 5.555 in., 141.0 mm.

Refracting angle of each prism 63° .

Again following the results of the calculations and experiments detailed in the publication previously referred to, the collimator objective was made of the regular Brashear Triplet form, and not of the Isokumatic form which absorbs too much light, and to prevent internal reflections and consequently loss of about 20 per cent of the light, was cemented with watch oil. This was tried at Ottawa but the low winter temperatures prevailing there congealed it and it was not usable. However, during its use at Victoria through the winter where the temperature rarely gets below freezing, the oil showed no signs of giving trouble in that regard and as the oil can not possibly induce strain as balsam is likely to do, it seems likely to answer every purpose. The aperture of the collimator objective is 2.5 inches, 63 mm., and its focal length 45 inches, 1143 mm.

The choice of central ray was taken considerably further to the violet than usual, at $\lambda 4200$. This was done to take better advantage of the number of lines in early type stars to the violet of this wave length while at the same time there are comparatively few to the red of $\lambda 4500$. Further, the lesser absorption of the O 118 glass in the violet and the absence of any absorbing material in the objective if the slight selective absorption of the silver coat be left out of account seemed to justify placing the central wave length at $\lambda 4200$. However, the adjustable nature of the spectrograph will readily admit of shifting the camera and prisms in a few minutes to any other position and with the same objectives it could be shifted to any other part of the photographic spectrum without the colour curve becoming unmanageably steep.

Three camera objectives were ordered from the Brashear Co. all of 3 inches, 76 mm., aperture. Two of these have been received, both of the Hastings Brashear Triplet form, one of 28 inches, 711 mm., focus and one of 38 inches, 940 mm., focus. Both of these objectives are oil cemented like the collimator and perform beautifully. The third objective is a short focus, one of the Cooke separated triplet type, of 15 inches, 381 mm., focus. This has not yet been received but is expected shortly.

The linear dispersions given by these cameras with the one, two, and three prisms ordered but not received are given in Table VII, and also the dispersion given by the 60° , O 118 prism now in use.

GUIDING APPARATUS

The guiding is done by the usual reflecting slit method, the jaws being inclined at an angle of $3\frac{1}{2}^\circ$. About 4 inches above the jaws is the guiding telescope parallel to the surface of the slit jaws, a reflecting prism at the inner end sending the diverging pencil from the slit along the tube of this telescope. A symmetrical triplet objective, adjustable by rack and pinion in the tube, has conjugate foci at the slit and ocular. Near the ocular the tube is broken a reflecting prism deviating the pencil 45° and this part of the tube can be revolved in the other for convenience in guiding.

SLIT AND DIAPHRAGM MECHANISM.

The slit jaws are of polished nickel, being much less liable to chipping and injury than the speculum metal previously used, and one of them is pushed away from the other against a spring by a micrometer screw reading to thousandths of an inch. The method of applying star and comparison spectrum is new and offers considerable advantage, I believe, over methods previously employed. Directly above the slit are two small right angled reflecting prisms which reflect the comparison light from its original direction, perpendicular to the optical axis of the spectrograph and also perpendicular to the slit, down through the slit. These prisms are placed with their edges parallel to the slit and can be brought into contact or separated symmetrically with respect to the centre of the length of the slit by means of a right and left hand screw. The cells which hold the prisms, the mechanism for separating them and consequently the prisms themselves, can be moved as a whole perpendicular to the slit, towards or from the comparison source. The prisms are held in their cells by thin metal plates which are just above and just clear the

slit jaws. These plates are accurately shaped as shown in the diagram, Fig. 17, and serve also as diaphragms to limit the length and position of star and comparison spectrum. The wedge shaped opening *a* between the two plates limits the length of star spectrum exposed and normally when the plates and prisms are in contact will give any length of spectrum from 0 to 0.5 mm. In order to allow the star light to pass through, a rectangular notch of sufficient width is made on the adjacent front corners of the prisms where they come over this wedge shaped opening. Just outside the wedge shaped opening rectangular openings *b, b*, about 1 mm. wide and 6 mm. long is made in each plate and these openings

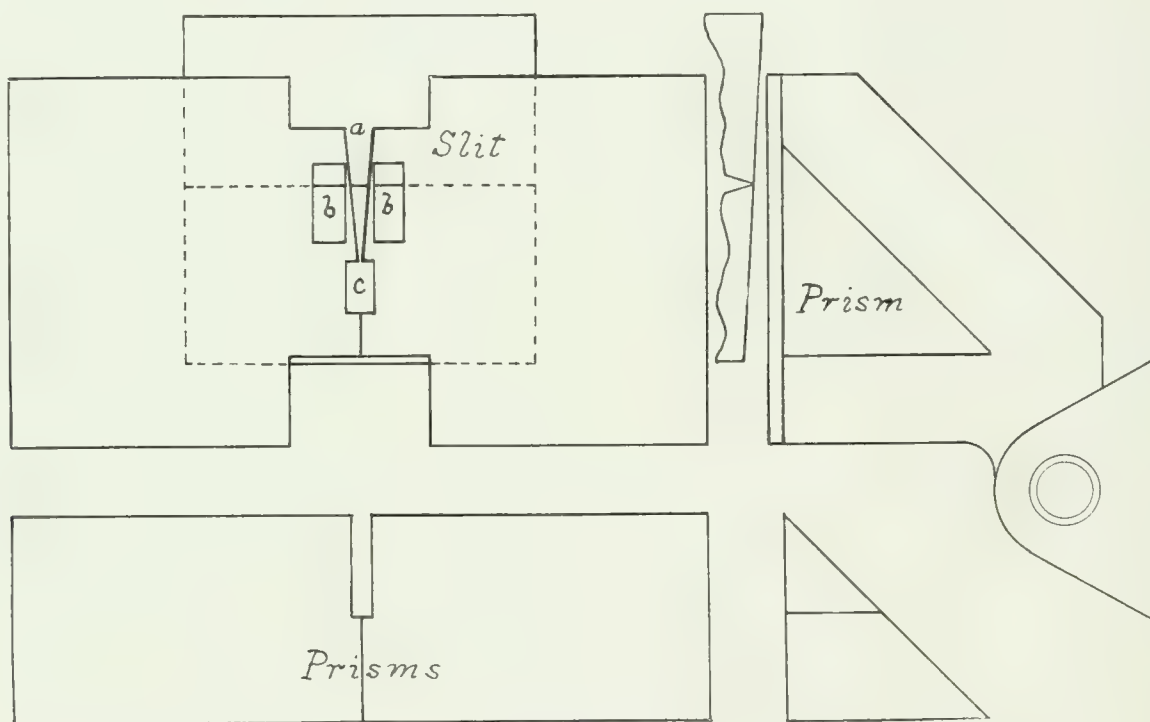


Fig. 17. Slit diaphragm and comparison prisms, three times natural size.

allow the comparison light, reflected from the hypotenuse of the prisms, to pass through the slit and form a comparison spectrum on each side of the star spectrum, perfectly symmetrical with respect to the latter, with lines always the same length and separation from one another so long as the distance apart of the prisms is not changed.

For all ordinary stellar spectral work the prisms and diaphragm plates will be in contact, and the width of the star spectrum may be adjusted to anything desired between 0 and 0.5 mm. by simply moving the prism mechanism across the slit by the rack and pinion until the desired width in the wedge opening is obtained. Three adjustable stop screws which can be turned in and out of engagement as desired serve to fix this lateral movement to any one of three positions, which evidently can be reproduced at will and without uncertainty or looking to the adjustment. At whatever width of star spectrum required within the above range the stop screw is set, the rectangular comparison openings

are above the slit, and the comparison can be turned on when and as often as desired without touching the slit head or changing the adjustment in any way and without stopping or interfering with the exposure on the star.

If nebular or planetary spectra are desired all that is required is to turn the right and left hand screw until the prisms and diaphragm plates are separated the diameter of the object, which can be carried to the full length of the slit, when the celestial and comparison spectra can be exposed as before and whatever the width of object the comparison spectra are always separated from it by the same distance.

A further convenience is provided in this diaphragm mechanism. Just back of the point of the wedge in the adjacent edges of the diaphragm plates two notches *c*, as shown in the figure are filed. The side of these notches are in line with the inner edges of the comparison openings so that if the diaphragm and pinion mechanism is moved forward by the rack and pinion until these notches are over the slit, a comparison spectrum can be made there, the ends of whose lines will just touch the inner ends of the lines of the outer regular comparison strips. Hence, by simply moving the prisms and diaphragm from one stop to another a single comparison spectrum, about a millimetre wide, can be placed between and touching two comparison spectra also about a millimetre each wide. This makes a very convenient and useful method of determining the camera focus by the Hartmann method of extra focal exposures. A simple shutter mechanism was placed just below the collimator objective so that by turning knurled knobs on the outside of the spectrograph box, either the front or rear half of the objective could be covered or left entirely unobstructed as desired. If now the camera focus be placed at any desired setting and the inner strip of comparison be exposed through the half of the prism containing the refracting edge and the outer strips through the base half, it is evident that, if the camera is at the correct focus, the spectrum lines will be continuous and if not they will be displaced. If another pair of exposures is made at a slightly different setting, and this can be done on the same plate by moving it transversely, preferably so that one is within and the other without the focus by 0.1 or 0.2 mm., by simple comparison of the relative displacements of the spectral lines in the two exposures, the correct focus can be estimated easily to 0.05 mm. This method of focussing the camera is more certain and accurate than by the definition test and can be carried out in a very few minutes.

This diaphragm mechanism offers all the advantages of Wright's comparison device where there are separate electrodes for each comparison spectrum placed in a prolongation of the slit and sending the light through the slit by small prisms with their edges perpendicular to the slit whose distance apart, which limits the length of star spectrum, can be adjusted as desired. Either device allows star and comparison to be exposed simultaneously and can be adjusted for any width of spectrum. But in the device on this slit head only one comparison source is required, which is permanently attached to the frame and entirely independent of the slit head. It is very easy to adjust and has the advantage over Wright's device in that the spectrum lines are perfectly uniform in intensity over the whole length in the two halves, a condition which is, I believe, very difficult to obtain in the other. Further, by a simple turn of a knurled head, adjacent comparison spectra for the Hartmann method of determining the camera focus can be obtained.

COMPARISON MECHANISM

As direct current at 220 volts was used in the electrical operation of the telescope, it seemed preferable to use the iron arc rather than the spark for comparison purposes, as being simpler and giving better lines. A slide with V-ways attached to the carrying frame of the spectrograph opposite the projecting cameras serves to carry the guiding telescope and the comparison mechanism and to adjust them vertically. The arc as at first devised, was made self striking by magnetic action as soon as the current was turned on but the magnetic field thereby produced tended to blow out the arc and it was finally struck by separating the electrodes, $\frac{3}{16}$ inch iron rods, by means of a rack and pinion while it was broken by turning off the current by a snap switch adjacent to the pinion shaft. The electrodes are vertical so that the image of the arc formed by a condensing lens with diffusing screens attached to the same adjustable base as the electrodes, is transverse to the slit. The arc works satisfactorily and silently with about 4 amperes of current and gives beautifully uniform and sharply defined lines without a trace of continuous spectrum. The time of exposure is very short but is readily increased to any desired amount, convenient in the division of the exposure time into a number of intervals, by interposing neutral tinted absorbing glasses in the path of the light.

THE SPECTROGRAPH BOX

As previously stated, the spectrograph box carrying all the optical parts is a self-contained unit and is carried and flexibly supported in collimation with the telescope by a surrounding frame to which it is attached at two points.

This box is arranged so that any one of the three cameras, short, medium and long focus may be used with one, two, or three prisms and the changes may be made with a minimum of trouble and a certainty of going into exact adjustment. In order that any region of the spectrum may be used the prisms are carried on a minimum deviation link-work with additional links which serve to maintain the cameras, whether used with one, two or three prisms, exactly along the optical axis whatever part of the spectrum is central.

The general shape of the box, which is a single aluminum casting, is well shown in the photograph of the spectrograph with the temperature case removed, Fig. 18. The circular shaped opening in the side, covered normally by the three plates shown on the floor, is directly over the prisms and link work. The three projections to the right are the places in which the cameras are inserted for use with one, two or three prisms, the medium focus camera for use with one prism being in place and the short focus camera standing on the floor. Another projection for carrying the collimator tube extends centrally up within the attaching frame and the whole box is stiffened by a box girder cast integrally between the third camera and the collimator projection. Owing to the whole box being in one casting with only the circular hole on one side as an opening it is exceedingly stiff, while, being made of aluminum, comparatively light. The collimator tube is of steel, being 3 inches in diameter. This material was selected as previous experience with similar types of lenses had shown that, with either one of the collimator or camera tubes of steel and the other of brass, the differential change of focus with change of tem-

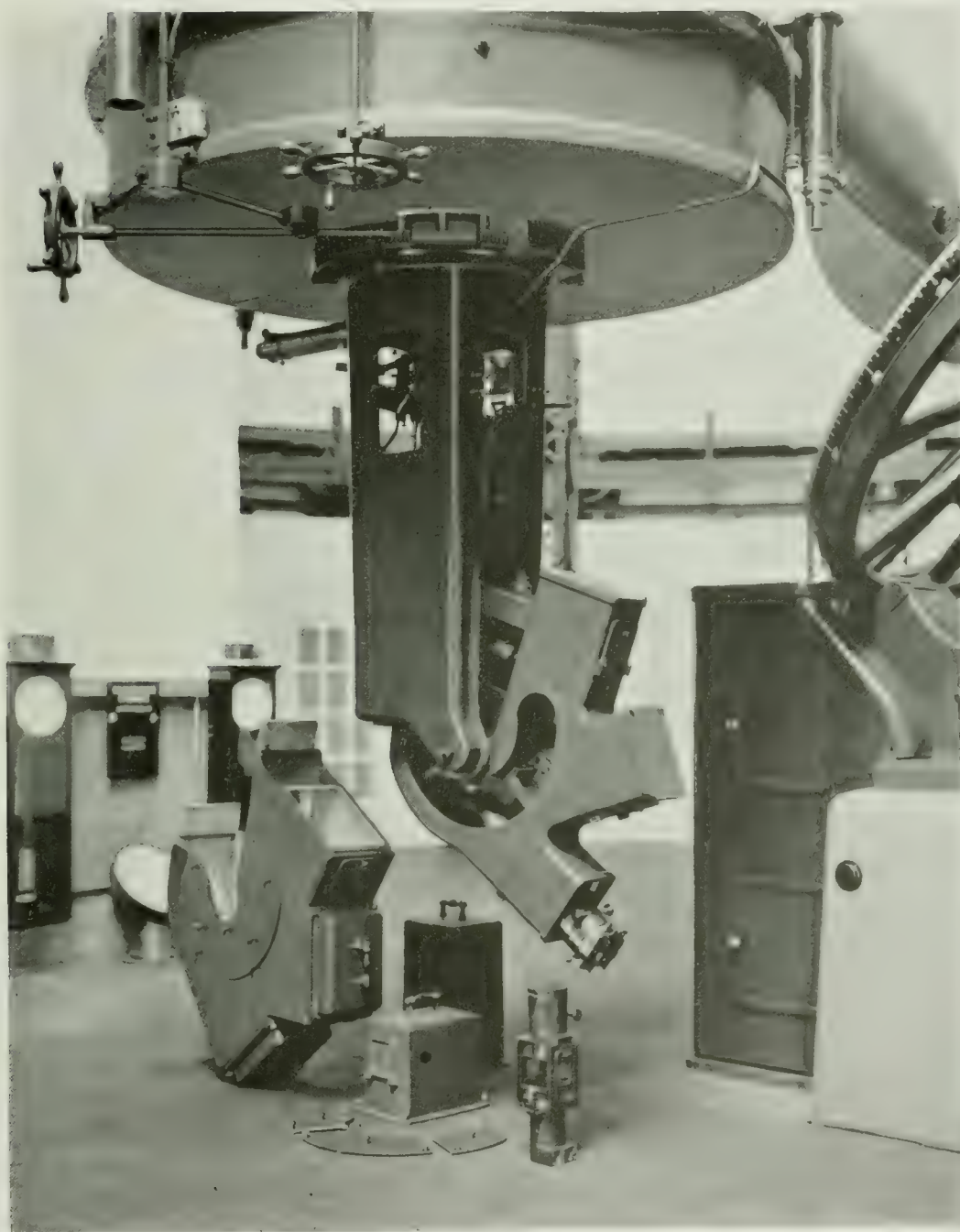


Fig. 18. Spectrograph with Temperature Case detached.

perature was vanishingly small. This has proved to be the case with this spectrograph as there is no appreciable change in the camera setting between 0 and 20 degrees Centigrade.

The minimum deviation link work which carries and adjusts the prism cells and prisms always at minimum deviation, whatever part of the spectrum is central, is similar to the link-work used by the Brashear Co. in their Universal Spectroscopes. It is exceptionally substantial and well made without any lost motion or backlash of any description. The fixed and movable gear sectors which operate the mechanism are pivoted to three substantial cast iron prism bases and these in turn are bolted through each of their three angles to the, at this part, $\frac{5}{8}$ in. thick base of the box. These bolts move in slotted holes in the base and before the spectroscope is to be changed so that any other wave length is central, these bolts and those holding the camera, must all be loosened. Then the camera, link-work and prisms can be together automatically moved to the new position and when the bolts are firmly clamped the whole optical system is as rigid and as little subject to flexure and change of adjustment, as if it were specially made for that one wave length only. The maintenance of position and adjustment depends only upon the clamping of the prism tables and camera firmly to the base of the box, the only function of the link work being to move prisms and camera together at the proper degree when the clamping bolts are loosened. In addition to the Brashear system of link work for the prisms, an additional element for guiding the camera is provided at each of the openings (when it is used with one, two or three prisms) so that it is always in line with the central ray, the one at minimum deviation.

On each of the prism tables, a prism cell of substantial construction is fastened with four screws while two dowel pins ensure its being replaced exactly in the original position when removed. For if one prism only is to be used, the second prism with its cell must be removed to allow the objective near the first prism. Similarly when two prisms are to be used the third prism must be removed. The prisms are held in position in the cells by three adjustable abutting strips at the base and a three-pointed sheet metal spring plate at the top whose pressure can be adjusted by a screw. The cells are put on the prism plates with the dowel pins and screws in place and the prisms are then adjusted on the cells in minimum deviation for one wave length and the abutting strips which fix their positions on the base of the cell firmly screwed home. The prisms will now always be in adjustment for any wave length and, if one has to be taken off, cell and prism are removed as a unit and can be replaced by aid of the dowel pins without disturbing the adjustment.

The cameras are each held rigidly in position by four bolts, two near the plate end and two near the objective end, passing through slotted holes in the base of the prism box, though they are guided by a slot in the link work engaging a corresponding key-shaped boss on the camera base, when the bolts are loosened. They are of exceptionally massive construction in order not to be subject to flexure and are designed for the greatest convenience in handling. The plate holders are of metal opening in the middle on a hinge, the plate 2 x 4 inches in size being held down against a raised surface at the edge of an opening $3\frac{3}{4}$ inches long and 1 inch wide on the front half by a spring on the back. They are hence supported parallel to the spectrum all along its length and less than half

DESCRIPTION OF BUILDING AND EQUIPMENT

an inch away from it and any curvature of the plates will have negligible influence on the focus or measures. The plate holder slides into a recess in its carrier where it is securely clamped by two thumb screws bearing against spring plates resting on its upper surface. As great care was taken that the distance from the margin on which the film is pressed to the front of the plate holder was the same in all four holders supplied, we may be sure that the plates are the same distance from the objective in every case. The plate holder carrier slides transversely in ways to enable a number of spectra to be made side by side on the same plate. An index and scale gives the position of the carrier while clamp screws hold it securely in any desired position. In addition, plate holder, carrier, and slide can be tilted 15° each way around an axis parallel to the spectrum lines so as to compensate for deviation of the focal plane of the spectrum from normality to the optical axis. This tilt can be read on a graduated sector and can be maintained by clamping screws. Focussing is effected by rack and pinion on the plate holder end of the camera, the objective being firmly screwed in an adapter at the other end and not being changed in position. The position is read by scale and vernier to tenths of a millimetre and can be maintained and displacement of the camera end by flexure avoided by an efficient clamping screw at each end of the telescoping tube by which the focussing is effected. The medium focus camera is shown in position for use as a one-prism spectrograph. The same plate holder and focussing end is used in the long focus tube by simply racking it out of the one and into the other which it fits equally well.

In the short focus camera the plate holder comes inside the projections on the spectrograph box and doors as shown are provided in the ends of these projections and in the temperature case for inserting the holder and drawing the slide. The general construction of the camera can be seen from the figure and the same adjustments for the plate holder as in the others are provided. This same camera would do for a 10 or 12 inch focus objective if such could be obtained by shortening the objective adapter which screws into the end resting on the floor.

THE ATTACHING FRAME

This, as well as the spectrograph box, is of cast aluminum and both are exceptionally fine castings. It is of hollow rectangular prism-shaped form with a substantial circular flange at the top, which is held by 8 screws firmly to the revolving cast iron ring at the lower end of the tube. There is an opening as shown at one side into which the prism box goes, the two sides coming down and embracing the box being of hollow box construction thus rendering the whole frame very stiff.

The spectrograph box is held in the frame by two shafts, the lower one seen centrally in the extension of the lower end of the frame being the principal support, while the upper one, which is within, principally serves to keep it from rotating on the lower shaft. The lower shaft passes through the box about centrally with respect to the optical system while the upper one is about two-thirds of the length of the collimator above it. Both of these shafts are so attached to the box that no relative flexure of box or frame can induce any strain whatever on the box and at the same time are adjustable in every direction horizontally to enable the optical axis of the collimator to be placed along the optical axis of the telescope. This was effected before the optical parts were installed by turning

the telescope truly vertical, hanging a steel plumb line down the exact centre of the tube and adjusting the two axes until it was exactly central at upper and lower ends of the collimator tube. Flexure will of course throw it slightly out of adjustment in other positions but this can not be avoided and is in any case an effect of the second order and will not cause appreciable error in the observations. The inside of the frame where it surrounds the collimator projection of the box is lined with felt half an inch thick and part of the heating wires are on the two inside walls in order to distribute heat uniformly all over the box.

THE TEMPERATURE CASE

The temperature case, which is shown put together but not attached to the spectrograph in Fig. 18, and attached in Fig. 19, has sheet aluminum sides and cast aluminum edges. It is beautifully fitted and firmly attached to the attaching frame but has no connection with nor does not touch the spectrograph box at any point. It is lined throughout and all the joints of the case, and of the doors and covers, carefully packed with felt $\frac{1}{2}$ inch thick and is hence very efficiently heat insulated.

There are three openings for the camera projections of the spectrograph box for which four covers are provided, two short to go over the openings in which no camera is placed, one intermediate for use with the short focus and medium focus cameras and one long for use with the long focus camera. Doors are provided in the two latter covers for inserting the plate holder and drawing the slide and doors in the edge of the case for similar operations with the short focus camera. A circular opening with cover is provided on each side of the case for getting at the prisms and clamping bolts so that all changes in adjustment may be made without removing the case.

The inside of the case is heated by passing the 110 volt lighting current through wire attached to the felt. There are three circuits, generally used in multiple, each containing about 110 feet of No. 20 double cotton covered German silver wire used for heating. Each of these circuits has a resistance of slightly over 50 ohms and will hence pass about 2 amperes of current giving 220 watts of heat. The three circuits will hence provide over 600 watts which is sufficient to keep the prism box about 30° C. above the surrounding air. As less than one-third of this difference between inside and outside temperatures will occur in practice, the current can be reduced by an external rheostat seen on the attaching frame but since removed to the switchboard for fear of radiation from it interfering with the definition of the star image. There are one of these circuits sewed on the felt uniformly over each side of the temperature case while the third is uniformly distributed over the far curved edge of the case which is parallel to the one prism camera and around the medium and long focus covers. Hence when the current is turned on heat is fairly uniformly supplied nearly all around the spectrograph box except at the top where it tends to rise by convection. To prevent stratification and ensure more uniform temperature throughout, the air within the case is stirred by a small electric fan whose body is seen between the third camera and collimator projections just below the box girder connecting the two, and to which it is attached.

The heat is turned on and off automatically by a mercury thermostat thermometer which actuates the armature of a relay which in turns moves a platinum point in and out

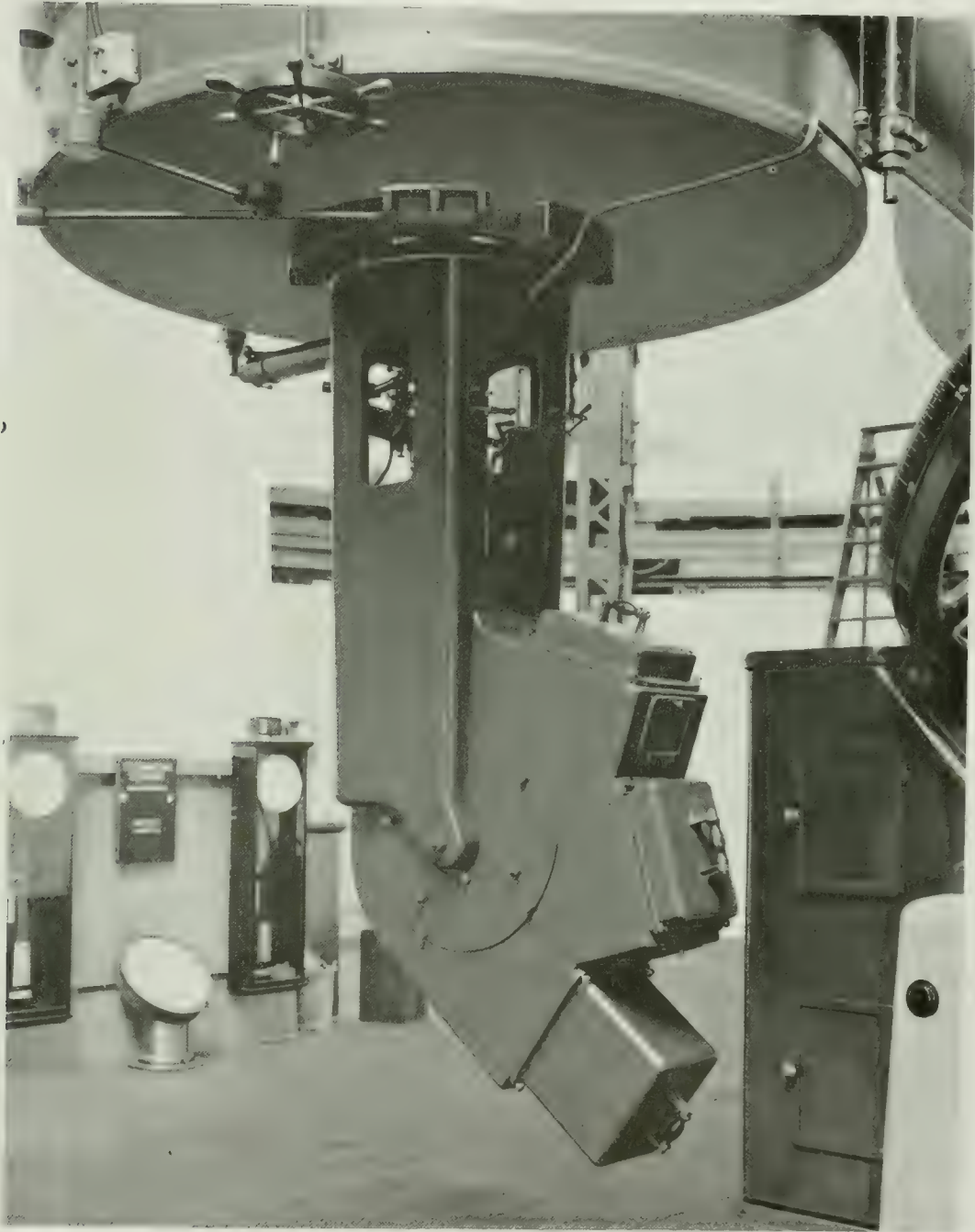


Fig. 19. Spectrograph with Temperature Case attached.

of a cup of mercury and thus turns the heating current on and off. It was intended to regulate and record the temperatures of the case and box by means of a Callendar Recorder, and this would make an eminently satisfactory procedure. But this instrument, like the prisms, was unobtainable during the war and in the meantime the present arrangement works satisfactorily. Explorations with a thermometer inside the case when the temperature there was 15° C. higher than that outside showed differences at extreme points inside not much greater than 1° and this would be much reduced in practice, when the difference between inside and outside would not normally exceed 5° . Further, owing to the very good heat insulation there seems to be no tendency to a general drop of the temperature inside the prism box as the difference between inside and outside temperatures increased, as was found at Ottawa.

The wiring to the spectrograph, consisting of thermostat circuit, fan circuit, heating circuit and arc circuit, comes from the terminal box near the bottom of the centre section in a cable and ends in binding posts on the attaching frame as shown. One of the knife switches shown is for the heating and the other for the arc circuit. The fan is controlled by a circular regulator switch seen below the rheostat. Rheostat and relay are now on the main switch board. When it is necessary to detach the spectrograph for resilvering the mirror all that is necessary is to detach the cable ends from the binding posts and slip it out from under the clips on the cell.

ATTACHMENT TO TELESCOPE

The spectrograph is attached to and detached from the telescope by a lever built of channel iron and forked at the outer end to embrace the rectangular part of the attaching frame directly under the flange. This lever has a pivot of cast steel which engages with the point of the rocker arm on the silvering car and extending beyond away from the telescope to a point over the main frame of the car to which it is attached by a threaded shaft and handwheel.

The telescope being turned until the tube is vertical and on the east side of the axis, the declination strut being run into place and the tube fastened at the top to prevent rotation when thrown out of balance by removing the weight of the spectrograph, the silvering car is run on its track until the forked end of the lever slips under the flange of the attaching frame, the bolts on those two flanges having been previously removed. The plunger of the car is then raised and the outer hand wheel adjusted until the weight of the spectrograph is relieved, when the other four holding bolts are removed, and the spectrograph lowered, by lowering the plunger and handwheel until it rests on a special wooden stand made to carry it when not on the telescope. The silvering car is then run back out of the way and the spectrograph and stand also wheeled out of the way to one side. The silvering car is then ready for removing the cell and mirror if desired or the telescope may be rebalanced if other attachments are to be used at the Cassegrain focus.

ADJUSTMENTS AND TESTS OF THE SPECTROGRAPH

The first procedure after the spectroscope was attached to the telescope was to place its optical axis along the optical axis of the telescope and this was done in a vertical position with a plumb line as previously described. The next procedure was to place

the slit at the principal focus of the collimator objective and for this purpose the collimator tube was removed from the spectrograph, set up on a table with the 60° prism and one of the cameras using a carbon arc as a source and the collimator focus determined by Schuster's method. Repeated trials succeeded in repeating the settings within 0.5 mm. and the slit was finally set at the mean position.

Replacing the collimator tube in the spectrograph the comparison apparatus was adjusted and with this as source the 60° prism was adjusted for minimum deviation at $\lambda 4200$. As the spectrograph was constructed for a mean deviation of 55° , which would be the deviation at $\lambda 4200$ of the 63° prisms of O 118 glass proposed for the instrument, and as the deviation of the 60° prism is only 50° , the slotted holes in the base of the prism box, carrying the link-work, prism bases, and one-prism camera had to be lengthened at one side, until the $\lambda 4200$ ray was central in the camera when the prism was adjusted for minimum. The camera was then carefully focussed and the plate holder placed at the proper inclination to have as long length as possible of the spectrum in focus. It was found that the field of the 711 mm., medium focus camera, was slightly convex towards the lens, the deviation from the tangent at $\lambda 4200$, at $\lambda 4600$ on one side and $\lambda 3900$ on the other being slightly less than 0.1 mm. It is probable, therefore, that with slightly greater angular dispersion such as that given by two prisms, the field would be flat. However, by accomodating slightly, the deviation at no position of the usable spectrum will be greater than 0.05 mm., which is too small to have any effect on the measures.

Tests were then made of change of camera focus with change of temperature and this was found to be quite inappreciable.

Tests of the flexure of the spectrograph in the single prism form were carried out in two ways, first by moving the telescope in declination and observing the displacement of adjacent comparison spectra made as before described and second by leaving it at fixed declination and moving it in R.A. This latter test which more nearly corresponds to actual observing conditions, showed no appreciable or measurable displacement for a movement in hour angle of 4 hours from the meridian, while the normal exposures will be much less than half of that. The movement in declination from vertical to horizontal or through 90° showed a displacement of some 10 kilometres which is relatively small for the single prism form where flexure has the greatest possible effect. In two-prism or three-prism form the flexure would only be a small fraction of the above and it may be concluded therefore, that flexure in any possible observing practice will have absolutely no effect.

CHAPTER VIII.—DESCRIPTION OF THE BUILDING AND DOME

THE BUILDING

It was early decided that the building and dome must be entirely of metal construction in order to more rapidly assume the temperature of the external air and prevent any "dome effects" from interfering with the "seeing". In order to avoid overheating the interior of the building by the direct rays of the sun a double covering was provided on both building and dome allowing continuous circulation of the air from openings at the base of the building to louvres at the top of the dome.

As previously stated, the designs of the building and of the concrete pier for supporting the telescope were worked out in the chief architect's office and are well proportioned and harmonious in design. The proportions of building and dome can be seen from the illustrations, Frontispiece and Fig. 20, and I do not believe can be improved much and the general effect of the structure, especially when it is remembered that it is constructed of sheet iron and the possible architectural effects thus limited, is very good.

The concrete pier is a massive structure of reinforced concrete, the north and south elements being connected by a reinforced arch below the observing floor and the north section, curved as shown in Fig. 11, to allow more room for swinging telescope and spectrograph below the axis, is supported by a latticed structural steel girder built up of 4 inch angles at each corner diagonally latticed from bottom to top. This was to enable the column to better resist the horizontal component of the thrust of the polar axis amounting to about 15 tons.

The framework of the building which rises 33 feet above the ground consists of 24 8-inch Bethlehem H columns tied together at the top by I beams on which is fastened the circular rail which carries the dome and on which the latter revolves.

The framework of the building is further stiffened by heavy diagonal bracing between four pairs of adjacent columns and the internal and external sheeting is attached by clips (to allow for expansion) to circular angles riveted at suitable spacing to the columns. The observing floor which is situated 21 ft. 6 in. above the ground floor, reached by iron stairs south of the telescope pier, is composed of checkered steel plates $\frac{7}{16}$ -inch thick supported by girders and columns entirely independent of the telescope pier which it does not touch at any point. This floor was designed to carry a load of 150 lbs. per square foot and is amply strong as even during the erection of the telescope no yielding at any place was evident.

The ground floor constructed of Terrazo is divided by temporary wooden partitions into dark room, sleeping room and two temporary offices and contains the motor generator set and main switchboard and the dome revolving motor and mechanism. The motor is a 15 H.P. three phase alternating current motor, operated by current supplied by the B.C. Electric Railway Co., and is directly connected to a 10 K.W. 220 volt direct current generator which operates the telescope and dome motors.



Fig. 20. Dome from North.

THE DOME

The dome is built up on a lower circular member 66 ft. in external diameter composed of two heavy circular angles latticed together to which is attached the revolving gear of the dome consisting of 24 roller bearing wheels carrying the weight of the dome and a series of external and internal lateral guide wheels all bearing on the turned circular rail which is mounted on the circular plate of the building. Two main ribs of deep section which serve to carry not only the secondary members of the dome but also the shutters and observing platform extend centrally across the dome from side to side separated by a distance of 16 feet. At 6 feet beyond the zenith these ribs are tied together by a cross member which serves to carry the secondary ribs below the shutter opening, the upper end of which is formed by this member. These main ribs are in reality double and of sufficient strength and rigidity to carry the whole weight of the dome and mechanism and in addition to bear the weight of the heavy parts of the telescope mechanism during erection. When the complete polar axis, about 14 tons in weight, was being hoisted, the deflection of these ribs as observed with a transit instrument was less than one-eighth of an inch. The structural frame of the dome is well shown in Fig. 21.

The secondary members of the dome are comparatively light yet rigid in construction, are spaced into a regular polygonal figure of 24 sides and are cross united inside and out by the small angles to which the internal and external coverings separated by an air space of 12 inches are attached. The skirting of the dome which extends below the hemispherical and cylindrical part of the dome, is carried by circular angles with supporting arms riveted to the lower member. This skirting is also double covered and ingeniously arranged in connection with the double weather guards to form a continuous passage for the internal circulating air from the double walls of the building to the double walls of the dome.

The shutters, which are of the usual double separating Warner & Swasey type, give a clear opening of 15 feet extending 6 feet beyond the zenith. They also are double covered with openings at bottom and top to permit circulation of the enclosed air. They move on roller bearing wheels running on horizontal girders at bottom and top of the shutter opening and are actuated by wire cables winding on a motor-operated drum. Canvas wind curtains stretched on tubes extending between the main ribs and rolling on guides attached to the latter can be operated one from the bottom upwards and the other from the top downwards so as to limit the length of the shutter opening to the diameter of the tube when a wind is blowing. These curtains are raised or lowered by the same motor that operates the shutters, clutches serving to connect or disconnect either at will. Motor and clutches are operated from a platform permanently attached to the lower member and right hand main rib of the dome at the level of the lower member. This platform is reached from the observing floor by an iron stairway with handrail also permanently attached to and rotating with the dome.

The main feature of this dome, however, and the principal one which makes it so much superior to previous designs is the observing platform. When the telescope is to be used for direct photography at the principal or Newtonian focus, it is evident that the observer must be able to have convenient access for guiding, etc., to the upper end of the



Fig. 21. Framework of Dome from North.

tube in any observing position. For the design of this platform and the perfection with which it fulfills the required purposes, we are indebted to the ingenuity and ability of Mr. E. P. Burrell, works manager of the Warner & Swasey Co. The problem was an especially difficult one owing to the form of mounting of the telescope, as the tube pivoted at one side of the polar axis and moving eccentrically with respect to the dome, made the motions of the upper end more complicated and the corresponding required positions of the platform much more numerous than is required with telescopes like the 60-inch and 100-inch where the axis of tube, the declination axis and the polar axis intersect. The solution of the problem was facilitated by the construction of a model, one-tenth size of telescope, building and dome for exhibition at the Panama Pacific Exposition, as in this model all possible positions and motions could be studied to scale and the design modified to conform to the requirements.

The observing platform of the 66-foot dome consists of a substantial structural frame about 22 ft. long and 4 ft. wide with a floor of $\frac{1}{8}$ inch plate. In its normal position when the telescope is used in the Cassegrain form, this platform is at the same level as the stationary platform already described and the observing platform is hence readily accessible. At each end of the platform are movable wings extending out into the dome about 6 ft. from the inner edge of the platform, semicircular in shape on the sides facing each other so as to enable the tube to be about two-thirds encircled when they are moved up to it. They are movable by means of roller bearing wheels longitudinally along the main girders of the platform and the observer by standing on either one of these movable platforms can, by means of a hand wheel, move himself and it with the greatest ease, longitudinally along the observing platform to any desired position and bring himself into a convenient position for guiding. These movable platforms are a great advance and enable the following and guiding to be done in most observing positions with the greatest ease. Both the main platform and the wings are completely enclosed by a tubular railing 30 inches high making it perfectly safe to move around on in the dark. The central section of this railing on the front of the main platform can be lifted out if desired, as is convenient in certain positions of the telescope, but in these positions the tube occupies the place of the railing and the safety character of the railing is preserved.

The platform including of course the movable wings, is pivoted by a rigid rectangular structural framework at each end to trolleys running on curved rails attached to the main ribs of the drum, the greater part of the weight of the platform, 11,000 lbs., being sustained by counterweights on similar trolleys running on an extension on the same curved rails down the main ribs on the opposite side of the dome. The platform is pivoted to the trolley at the upper corner of the rectangular frame work and would not remain horizontal unless it were supported at the upper inner corner of the frame. The horizontality of the platform is maintained without appreciable deviation as it moves in its curved path up the dome by an equalizing cable attached to a drum, on the same shaft as the hoisting drum but of a different diameter. These diameters are so proportioned that, over the 70° arc the platform moves, it remains very nearly horizontal and can be moved up and down to any desired position with the greatest smoothness. This motion is controlled by operating handle and rheostat on the platform itself by which the speed can be varied between 1.5 and 6 ft. per minute.

A pivoted iron stairway whose weight is counterweighted, is attached to the stationary platform and when the observing platform is not in use is drawn up against the roof of the dome entirely out of the way of the telescope. When the observing platform is used this stairway is let down to the bottom of its movement determined by chains attached to the top of the stairway and to the roof of the dome directly above. In this position a handrail attached to the dome is in a suitable position to enable the observer to walk with perfect confidence and safety up and down to the observing platform in any possible position. It is hence not necessary to change the position of the platform in order to get to or from the observing floor and direct photography can be carried on with the greatest possible convenience, ease and safety. A general view of the observing platform and accessories in position for work at the Newtonian focus is shown in Fig. 22.

The dome is revolved at the rate of 60° per minute by means of an endless cable stretched around the interior corner of a circular angle attached to the lower member. This cable is led off by two guiding pulleys over a V-shaped groove in a motor driven wheel, on the ground floor, the correct tension and friction being maintained by a counterweighted idler pulley. The motor is controlled by either one of two operating handles on the auxiliary switchboards on the east and west sides of the south pier directly adjacent to the operating handles for the quick motions of the telescope. Current is led to the shutter-curtain and to the elevator motors by means of two circular trolley wires carried entirely around the dome and attached to the same supports that carry the revolving cable angle, and by trolleys attached to the building conveying the current to these wires.

The whole dome and accessories operate smoothly and comparatively noiselessly, especially since the original steel pinions on the motor shafts have been replaced by Bakelite. Indeed the whole mechanical equipment is so perfected and so convenient in use that it is a constant joy to operate.

CONCLUSION

It suffices to say in conclusion that the test of a year's actual operation of the telescope has shown it to be even more accurate, satisfactory and convenient in operation than had been anticipated. The quality of the optical parts is well shown in the results of the Hartmann tests, in the short exposures required for the spectrograph, and in the remarkable smallness and crispness of the star images in the direct photographs. As previously stated, the driving is perfect and no trace whatever of any period or irregularity in the following has been detected. The arrangements provided for operating the telescope, for setting on the star, work to perfection and I have yet to find any part of the design where any improvement could be suggested. In making exposures on star spectra the average time required in changing from one star to the next, from the end of the exposure on one star to the beginning of the next is less than three minutes and if the stars are not far apart is generally only two minutes. I do not believe that record is excelled by even very small telescopes and, when we consider that the moving parts weigh 45 tons, the ease of handling is a remarkable evidence of the perfection of design and workmanship.



Fig. 22. Telescope and Platform in position for Direct Photography.

Besides being at present the largest telescope in operation, this instrument in optical and mechanical perfection, in convenience and speed of operating, is, in my opinion, unequalled in the world. Canada is to be congratulated on the enterprise which led to the construction and completion, under difficult circumstances of this instrument, a telescope more than twice as large as in any other national observatory, and one from which great advances in astronomical science may be expected. It is in such additions to the cause of pure scientific research that the real progress of a country may be truly judged and if, as has been often said, the degree of civilization of a nation is measured by its support of Astronomy, Canada takes high rank and all Canadians should be proud of the position their country has taken and now holds in astronomical research.

Dominion Astrophysical Observatory, Victoria.

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THE SPECTROSCOPIC BINARY 12 LACERTAE

BY REYNOLD K. YOUNG

Twelve Lacertae belongs to the same class of binaries as β Cephei, σ Scorpii and β Canis Majoris. These stars are similar in having very short periods ($4\frac{1}{2}$ to 6 hrs.). All of them are probably variable and their radial velocity curves without exception present peculiarities. An orbit for 12 Lacertae has already been published by the writer in the publications of the Dominion Observatory¹ Volume 3, No. 3. This work was based on measures of 117 plates taken at Ottawa with the one-prism spectrograph of that Observatory. The fact that the period proved to be only four times the time required to obtain a single spectrum made the investigation of the finer details of the behavior of the star's light extremely difficult. Nevertheless the observations did bring out several points of interest and indicated that it would be worth while to pursue the investigation further when an instrument for which the exposure time was shorter was available.

The one-prism spectrograph attached to the 72-inch reflecting telescope will secure a good spectrum of 12 Lacertae, under normal exposing conditions, in five minutes. In the following work, the slit has been set narrower and the spectrum made wider than usual. Ten minutes under these conditions give a strong spectrum extending into the violet well beyond K. Twenty-five to thirty spectrograms can therefore be secured during one revolution of the star. We have secured two series of plates covering a complete period, one series taken August 27 and a second series taken September 2. Plates were taken on three other nights near the times of predicted maxima or minima. This data is given below in Table I.

TABLE I.

Plate No.	Date 1918	Phase	V	Vel. from K Line	Width of Lines	Plate No.	Date 1918	Phase	V	Vel. from K Line	Width of Lines
	Aug. 27										
505	.793	.021	- 9.7	-11.2	61	511	.835	.063	+ 0.2	-20.9	84
506	.799	.027	- 6.8	-23.6	65	512	.842	.070	- 2.9	-18.0	105
507	.806	.034	- 0.7	-27.2	69	513	.850	.078	- 5.5	-21.0	103
508	.812	.040	+ 6.1	- 9.9	75	514	.858	.086	- 9.9	-20.2	106
509	.819	.047	- 0.7	-23.6	77	515	.866	.094	-19.9	- 7.4	117
510	.827	.055	+ 4.3	- 6.0	72	516	.874	.102	-18.3	-26.4	96

¹ cf. also Jour. R.A.S.C. Sept. 1916.

TABLE I—*Concluded*

Plate No.	Date 1918	Phase	V	Vel. from K Line	Width of Lines	Plate No.	Date No.	Phase	V	Vel. from K Line	Width of Lines
517	.880	.108	-21.4	-16.2	86	553	.850	.092	-15.1	-16.9	100
518	.888	.116	-35.2	-33.5	81	554	.859	.101	-23.5	-14.2	107
519	.895	.123	-29.3	-17.5	81	555	.868	.110	-31.6	-21.3	102
520	.902	.130	-37.1	-15.8	85	556	.877	.119	-51.3	-35.5	96
521	.913	.141	-37.9	-22.5	68	557	.886	.128	-64.3	-38.1	91
522	.921	.149	-43.1	-16.8	63	Sept. 11					
523	.928	.156	-40.0	-26.9	65	574	.755	.115	-41.0	-17.2	106
524	.936	.164	-36.8	-20.3	70	575	.765	.125	-42.1		87
525	.944	.172	-31.6	-26.7	82	576	.776	.136	-45.5	-22.6	106
526	.951	.179	-25.3	-10.8	65	577	.786	.146	-39.4	-16.4	76
527	.958	.186	-20.2	-15.0	64	579	.860	.027	- 0.1	-11.7	74
528	.967	.002	-22.5	-16.5	65	580	.868	.035	+ 6.0	-13.4	63
529	.974	.009	-16.7	-16.8	66	581	.879	.046	+12.5	+ 3.0	
Sept. 2						582	.890	.057	+13.3	- 7.2	
539	.705	.140	-46.3	-17.9	91	Sept. 13					
540	.712	.147	-48.8	-29.2	80	591	.787	.023	- 9.5	-25.5	63
541	.720	.155	-53.3	-25.4	66	592	.799	.035	-10.8	- 7.9	77
542	.732	.167	-42.3	-37.3	68	593	.808	.044	-10.4	-15.4	76
543	.740	.175	-39.5	-20.5	53	594	.819	.055	-16.9	-13.2	85
544	.747	.182	-27.0	-21.0	62	598	.899	.135	-29.9	-26.0	98
545	.761	.003	-23.5	-21.1	54	599	.909	.145	-18.2	-22.0	83
546	.769	.011	-11.3	-18.9	57	600	.919	.155	-30.4	-18.5	82
547	.777	.019	- 7.8	-11.4	73	Oct. 19					
548	.790	.032	+ 3.4	- 2.5	86	702	.624	.138	-36.6	-20.1	75
549	.798	.040	+11.0	- 6.3	73	703	.634	.148	-31.1	-16.6	69
550	.808	.050	+ 7.3	+ 0.9	62	709	.717	.038	- 0.9	- 7.7	50
551	.832	.074	+15.5	-15.9	89	710	.726	.047	- 1.9	-10.5	62
552	.841	.083	+ 6.9	- 8.3	85						

In the third column of the table, the phases are counted from Julian Day 2,421,833.0. The fourth column gives the velocities obtained from all the spectral lines, exclusive of the lines H and K of Calcium. The results from the latter lines are found in the fifth column. As a rule the K line alone was measurable. The sixth column gives the sum of the widths of eight of the principal lines, the unit being $\frac{1}{200}$ th mm.

A general idea of the precision of the measures may be obtained from an inspection of the radial velocity curves for August 27 and September 2. The points indicated in these curves are normal places, each formed from two to three individual measures. The probable error of a single observation as determined graphically was 1.9 km. for August 27 and 3.2 km. for September 2.

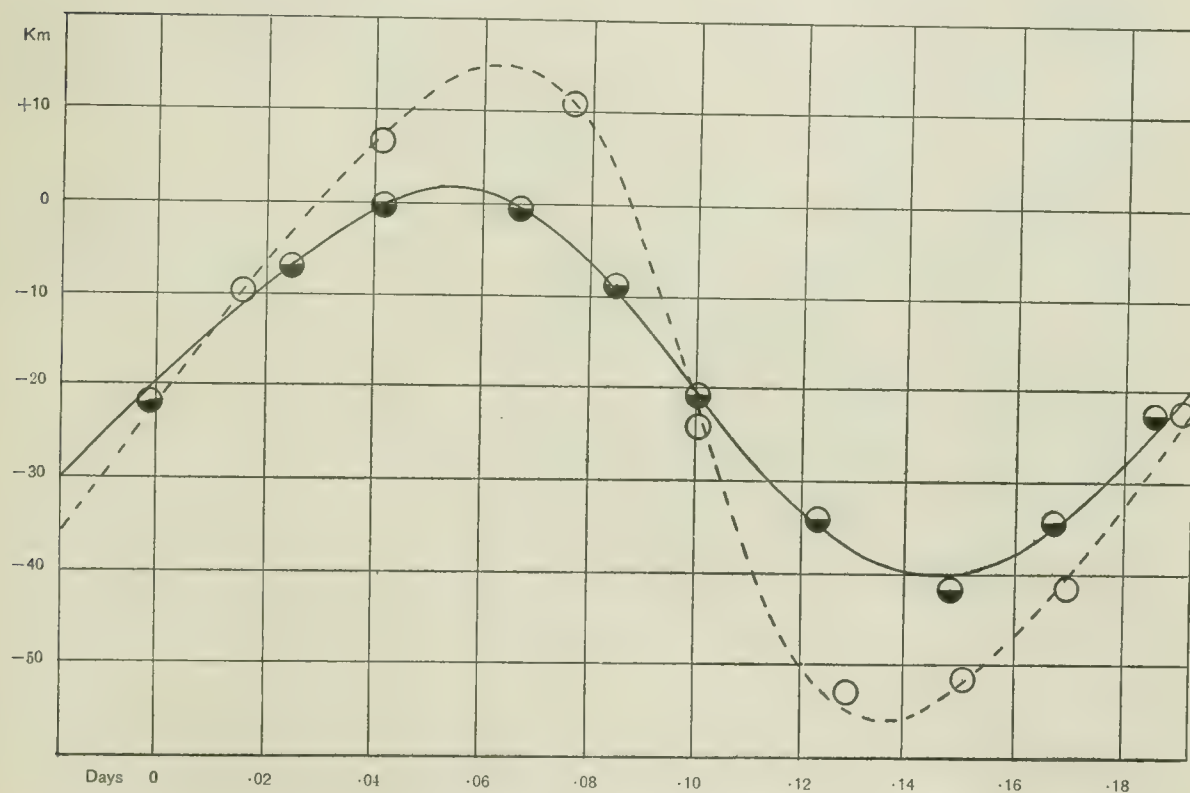
Insert Fig. I.

Period. The period previously published rested on observations taken during the years 1913, 1914, 1915 and a few plates taken at the Mt. Wilson Observatory in 1911. Since then Professor Frost, Director of the Yerkes Observatory has communicated three additional velocities, the earliest taken in 1908. The last plates here were made over ten years later, so that from the date of the first observation here, the star has made more than 19,000 revolutions. There are no indications that the old period should be

altered unless it were to add a cipher. The period $\cdot 1930890$ day seems quite satisfactory. Radial velocity curves made on different nights show that the amplitude and shape of the curve vary. It is difficult in a star of this nature to be sure that the correct number of cycles have been assumed to have taken place between individual observations separated by long intervals. It seems unlikely that a mistake has been made for observations in eight out of ten consecutive years agree reasonably well with the mean curve.

The variation in the amplitude of the orbit as well as in the shape of the radial velocity curve is shown by the observations of August 27 and September 2 as plotted in Fig. I. These observations yield the following elements:—

August 27		September 2	
P	$\cdot 1930890$		$\cdot 1930890$
e	$\cdot 10$		$\cdot 20$
T	J. D. 2,421,833 $\cdot 100$		J. D. 2,421,833 $\cdot 100$
K	20 $\cdot 5$ Km.		35 Km.
	$-20\cdot 4$ Km.		-20 Km.



Radial Velocity Curves of 12 Lacertae
August 27 and September 2
Fig. I

These two sets of elements differ in the eccentricity and in the amplitude only, for the agreement of the values of γ is well within the probable error and the two values for the time of periastron passage are identical. The observations made on September 11, 13 and October 19 furnish further proof that the velocity of the centre of mass for all the measures made during 1918 has been constant. They show also that maximum and minimum velocity occur on schedule time. While there is some uncertainty in drawing a curve through observations when maximum and minimum are the only points given, especially those taken September 13, there can be no doubt that the amplitude varies between wide limits probably from seven or eight kilometers to thirty-five or more. This is well shown in Figs. 2, 3, 4.

The behaviour of 12 Lacertae in this respect recalls that of the spectroscopic binary β Canis Majoris. The orbit of this star has been very carefully investigated by Mr. Henroteau². In β Canis Majoris not only does the amplitude vary but a simple period fails to predict the maximum and minimum points. Mr. Henroteau gives a very ingenious explanation to account for the observations. He supposes "two sinusoidal or periodic variations of approximately the same constant amplitude and very nearly the same period exist". Their combination gives us a curve of variable amplitude with a constant value for the velocity of the system. When the two variations reinforce each other, i.e. when they are in like phase, then we get a large observed range. The fact that the two variations have unlike periods will soon alter this agreement in phase and when the phases differ by 180° then we observe small amplitudes.

In the case of β Canis Majoris there was evidence of the existence of this second period in the variation in the width of the lines. In 1915 the writer suspected that the lines in the spectrum of 12 Lacertae altered their character at times but the long exposures and the poor quality of many of the plates prevented this point being investigated. The present series of plates show that not only do the lines become diffuse but like the lines in the spectrum of β Canis Majoris they become wider. Figures 5 and 6 are plots of the measured widths of the lines in the plates taken August 27 and September 2. They show that in these two cases minimum width agrees almost exactly with periastron passage. In this respect the spectrum of 12 Lacertae parallels that of σ Scorpii another binary of very short period. A further inspection of the plates shows that when the range is small the lines are fairly wide and always rather diffuse. There is, however, no evidence as yet that the variation in the width and definition of the lines has a period different from that of the velocity variation although it is possible that such is the case. The evidence is not conclusive on this point.

There are other complications in the spectral measures of 12 Lacertae not yet recorded. If we compare the elements as derived from the 1918 plates with those published in 1915, we find that the velocity of the centre of mass seems to have shifted from 13.7 km. to nearly 20 km. In order to investigate this point more fully and make sure it was real, the observations taken in 1913, 1914, 1915, 1918 were examined separately. First, the straight algebraic means were taken. If the observations were distributed at random this would give the value of γ . Second, the observations were divided for each year into two parts. The first part comprising all those observations with phases where the binary

² L. O.B. Vol. IX, p. 155.

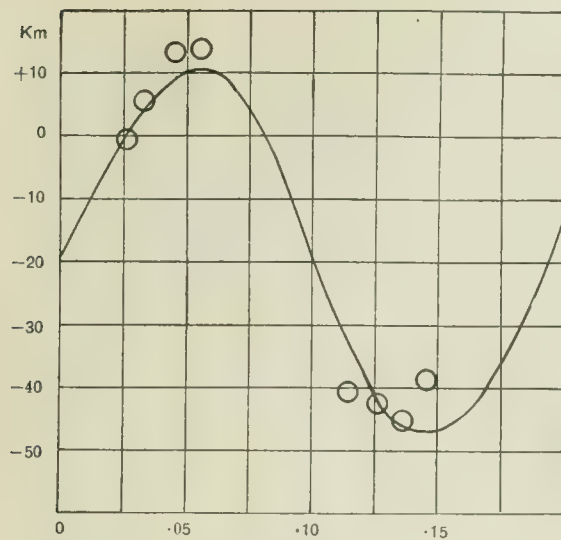


Fig. 2, September 11

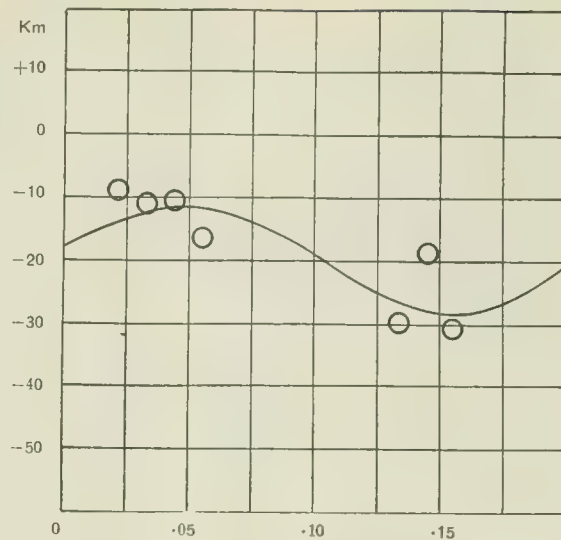


Fig. 3, September 13

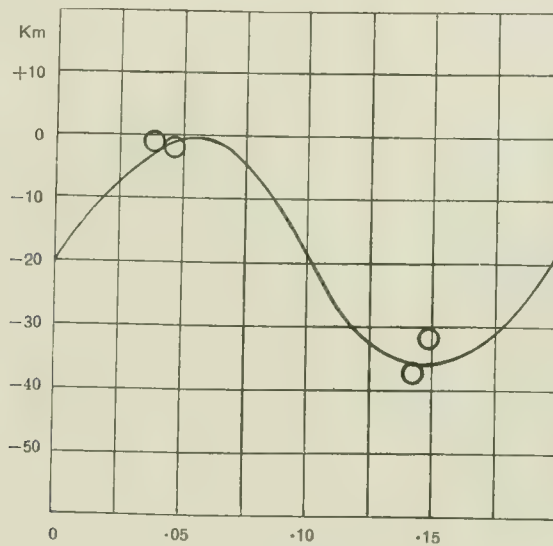
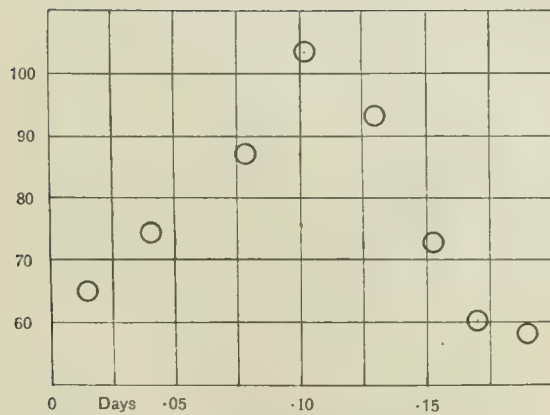
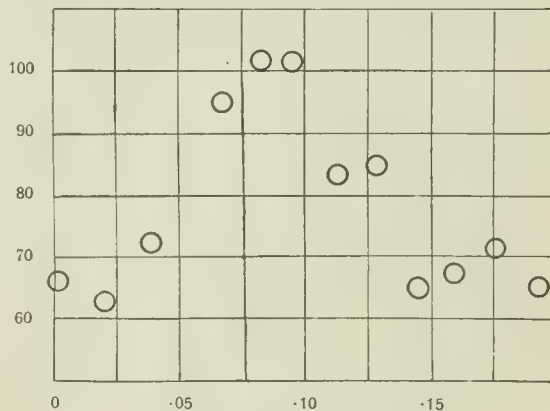


Fig. 4, October 19



Variation in Line Width
September 2



Variation in Line Width
August 27

was approaching us and the second those observations with phases where it was receding. The means of these were taken separately and then the mean of the two values should give a value for γ . This procedure eliminates an error which would be present in the first method from more observations lying below the axis than above or vice versa. Third, means were taken of a number of observations with phases centered around the maximum and minimum points of the radial velocity curves. This is probably the best procedure when, as in the present case, the eccentricity is small and ω nearly ninety degrees. The result is shown in the following table.

Date.	(1)	(2)	(3)
1913	-13.3 Km.	- 9.9 Km.	- 8.5 Km.
1914	-13.8 "	-12.5 "	-11.2 "
1915	-16.8 "	-15.4 "	-15.6 "
1918	-19.6 "	-19.3 "	-19.1 "

The centre of mass of the binary system 12 Lacertae is approaching the observer at a variable rate. The period suggested is many years. There is a distant companion 72" away, twelfth magnitude. It would hardly appear that this could be concerned in the phenomena as in the past century the relative motion has been very small.

Calcium lines. Since the discovery of the existence of binary stars in which the H and K lines did not share in the variation of the other lines, there has been considerable investigation to find out whether the calcium causing the absorption were surrounding the star as part of its atmosphere or whether it was in the form of a cloud lying between the observer and the star under observation.

The observations of 12 Lacertae, 1918, agree with those taken in Ottawa in showing that the calcium lines do not share in the same variation in amplitude as the other lines in the spectrum. On August 27 there is scarcely any range indicated. On September 2 the range is not more than twenty-five kilometers, while the other lines show a range of seventy. When the amplitude of the hydrogen and helium spectral lines is large, the calcium lines show a measurable smaller amplitude. When the hydrogen and helium lines are oscillating through a small range, the amplitude of the K and H lines, is either zero or masked by the errors of measurement. The velocity of the centre of mass of the binary system as determined from the calcium lines is in substantial agreement with that determined from the other lines. This holds for each year observation. Thus we have:—

	1913	1914	1915	1918
H and He	-8.5	-11.2	-15.6	-19.1
Ca	-8.0	- 9.1	-11.2	-17.7

The wave length of the Calcium lines if increased slightly would remove the systematic difference. The point that is significant is that the calcium lines strengthen the result, if indeed that needs strengthening, that the velocity of the centre of mass has varied since 1913. Moreover this variation shows in the *clearest way that the calcium vapours causing the absorption are moving with the star.*

One other point is worth recording from this investigation. The calcium lines show very little variation or character such as is shown by the other spectral lines. Whether we regard stars of this class as true binaries or whether we ascribe the variation in the

observed radial velocity to some pulsation of a single star as suggested by Shapley,³ the calcium vapour as a huge cloud surrounding the condensation or condensations in the centre is not greatly disturbed by the revolution within, if the star is a binary or by the pulsations of the core if it be but a single star. On the hypothesis that there are two condensations and that the cloud rotates around their common centre of gravity with a period coincident with the revolution of the stars in the centre it is possible to explain⁴ very nicely both the cases of apparently stationary H and K and those cases where these lines share in part of the variation of the other lines in the spectrum by assuming different degrees of condensation for the calcium vapour. The phenomena can, however, be explained equally well by the pulsation theory, assuming that the absorption which gives rise to the calcium lines occurs at a very high level and that the outer layers of the calcium cloud are not greatly disturbed by the pulsation taking place in the core.

Summary.

1. From the measures of spectra of 12 Lacertae taken in 1918 it is definitely shown that the amplitude of the radial velocity curve varies from night to night, being as small as fifteen or twenty kilometers at some times and as large as seventy at others.

2. The shape of the curve is not constant but a simple period will harmonize fairly satisfactorily the observations taken between 1908 and 1918 and serves to predict the approximate times of maximum and minimum velocities.

3. The spectral lines undergo a periodic variation in width, the lines being wide and diffuse at periastron passage and sharper and narrower at apastron. When the amplitude exhibited by the curve is small the lines are generally more diffuse than when the range is large.

4. The velocity of the centre of gravity as determined from plates taken in any one year is constant but plates taken in 1913, 1914, 1915 and 1918 show that it is subject to a long period variation.

5. The amplitude exhibited by the calcium lines is smaller than for the other spectral lines and they are always sharp and narrow even when the others have become wide and diffuse. When the range in the hydrogen and helium lines is high then the amplitude exhibited by the calcium lines is easily discernable, when the hydrogen and helium lines show a small range, the amplitude exhibited by the calcium is masked more or less completely by the error of determination.

6. The velocity of the centre of mass as determined from the calcium lines shows the same variation from year to year as do the other lines in the spectral. *This shows very plainly that the calcium causing the absorption is moving with the star and that therefore it is probably in the form of a large cloud surrounding it.*

³Contr. Mt. Wilson Sol. Obs. No. 92.

⁴Jour. R.A.S.C. Sept. 1916, p. 372.

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THE SPECTROSCOPIC BINARY H. R. 8170

BY J. S. PLASKETT.

This star in Cygnus of R. A. 21 h 17.2 m., Dec. $+39^{\circ} 55'$ (1900), of spectral type F8 and photographic magnitude 6.96, is the first spectroscopic binary to be discovered and have the elements of its orbit determined at Victoria. It is of interest on account of its short period and large range, rather unusual in stars of this type, and it was these characteristics, evident on the measurements of the first two or three plates, that led to the securing of observations for the determination of the orbit.

There is, however, a further interest attached to this orbit on account of the evidence it presents as to the quality of the work obtainable by the telescope and spectrograph at the new observatory. In consequence, the details have been arranged and the solutions carried through with this end in view.

The star, whose discovery was announced in the *Journal R.A.S.C.*, 13, p. 59, was placed on the radial velocity programme last August, the first plate being secured on August 23. Measurement of the first four plates early in November showed it to be of large range and short period, and further observations were obtained as often as possible between Nov. 23 and Dec. 23. In all, 15 plates have been used in determining the elements and although four months may seem a short time to obtain a final period, there have been nearly 40 cycles in that interval, while the large range and the accuracy of the observations make it relatively closely determined, the probable error of the period being less than three ten-thousandths of a day.

All the spectra have been secured by the new spectrograph of the observatory, arranged for use with one prism and a camera of medium focus. The linear dispersion given by this combination at $H\gamma$ is about 35 Å per millimetre. The plates have all been measured on the Hartmann spectro-comparator, which experience here has shown will give in stars of the F or later types, measures equally or more accurate than on the micrometer microscope, and in considerably less time.

After the preliminary publication of this orbit in the *Journal R.A.S.C.* XIII, p. 174 the velocities of the standards used on the comparator were carefully redetermined owing to an error found in computing the velocity of Mars. Consequently, the velocities of the plates and the velocity of the system given in the publication above have been changed by the addition of -1.28 km to each.

In Table I, the data of the observations and measures of the 15 plates used are given. In the first column is contained the serial number of the plate, in the second the date and in the third the Julian date of the observations. The fourth column gives the exposure time in minutes, the fifth the phase from periastron and the sixth the measured velocity reduced to the sun. The seventh and eighth columns contain the residuals of the individual plates, in the sense observed minus computed, from the preliminary and final orbits.

TABLE I.—OBSERVATIONS OF H. R. 8170.

Plate Number	Date		Julian Date	Exposure Time	Phase	Velocity	Residuals O-C	
							Prelim.	Final
	1918			m.				
478	Aug	23	2,421,829.826	20	2.330	-16.93	-1.98	-0.96
661	Oct.	8	875.713	19	2.809	+39.66	+0.77	+0.35
691	"	13	880.677	17	1.286	-47.30	-0.60	+0.07
706	"	19	886.677	21	0.799	-1.79	-0.21	+0.93
933	Nov.	23	921.562	28	0.006	+63.61	-0.49	-0.13
939	"	24	922.568	19	1.012	-23.01	-1.24	-2.01
963	"	26	924.553	18	2.997	-53.92	-0.28	+2.05
990	"	30	928.561	18	0.518	-35.95	+0.65	+0.77
1033	Dec.	11	939.569	19	1.796	-56.79	+0.09	+1.47
1043	"	15	943.587	25	2.571	-14.72	+4.55	+1.91
1078	"	20	948.544	16	1.041	-23.75	+0.35	+1.37
1084	"	20	948.628	20	1.125	-34.40	-2.00	-1.10
1106	"	21	949.560	23	2.057	-43.38	+0.17	-0.15
1110	"	21	949.662	25	2.159	-36.18	-1.03	-2.06
1128	"	23	951.552	20	0.805	-2.94	+0.21	+0.77

Some little difficulty in obtaining the preliminary period was encountered, but when this was determined the remainder of the work followed the usual course. Preliminary elements which were obtained graphically are given in Table III. the resulting residuals appearing in Table I. Examination of these residuals showed that these elements were probably not as good as could be obtained, and a least squares solution, using the differential co-efficients obtained by Lehmann-Filhés, was applied. Owing to the small value of the eccentricity, it was not considered advisable to use co-efficients for both T and ω , consequently the former was considered fixed at J. D. 2,421,801.549, while corrections were calculated for the period, eccentricity, amplitude, longitude of the apse and velocity of the system. The application of a correction for the period rendered it advisable to use the plates singly and not combine them into normal places, and although this might have been done for the two cases when two plates were obtained on the same night, it was considered more direct and satisfactory to treat all the observations separately.

The resulting observation equations, all of equal weight, are given in Table II in which the unknowns x, y, z, u, v have the following values.

$$\begin{aligned}
 x &= \delta\gamma \\
 y &= \delta K \\
 z &= K\delta e \\
 u &= K\delta\omega \\
 &\quad 100 K \\
 v &= \frac{\delta\mu}{(1-e^2)^{\frac{3}{2}}}
 \end{aligned}$$

TABLE II—OBSERVATION EQUATIONS OF H. R. 8170

1.....	1.000x	+ .570y	-.455z	-.848u	-1.123v	-0.65 = 0
2.....	1.000	+ .040	-1.003	-1.000	-1.500	-0.21
3.....	1.000	+ .022	-1.002	-1.000	-.850	-0.21
4.....	1.000	-.358	-.673	-.917	-1.075	+1.24
5.....	1.000	-.395	-.609	-.900	-1.277	-0.35
6.....	1.000	-.530	-.336	-.821	-1.153	+2.00
7.....	1.000	-.763	+ .299	-.596	-.442	+0.60
8.....	1.000	-.928	+ .877	+ .250	+ .319	-0.09
9.....	1.000	-.712	+ .143	+ .659	+ .918	-0.17
10.....	1.000	-.575	-.227	+ .788	+1.097	+1.03
11.....	1.000	-.246	-.829	+ .958	+ .265	+1.98
12.....	1.000	+ .162	-.978	+ .992	+1.423	-4.55
13.....	1.000	+ .629	-.321	+ .808	+ .628	-0.77
14.....	1.000	+ .878	+ .393	+ .546	+ .717	+0.28
15.....	1.000	+1.039	+ .996	+ .046	+ .060	+0.49

From the observation equations the following normal equations were obtained.

$$\begin{aligned}
 15.000x - 1.1679y - 3.7286z - 1.0342u - 1.9941v + 0.62 &= 0 \\
 + 5.5063 + .5463 + .8348 + .7917 - 3.5489 &= 0 \\
 + 6.9807 + 2.0229 + 3.3135 + 2.9223 &= 0 \\
 + 9.3758 + 10.7671 - 4.2403 &= 0 \\
 + 13.7039 - 7.4965 &= 0
 \end{aligned}$$

whose solution gave the following corrections

$$\begin{array}{lll}
 x = - .0603 & \text{or} & \delta\gamma = -0.06 \quad \pm 0.29 \text{ km.} \\
 y = + .7322 & & \delta K = +0.73 \quad \pm 0.46 \text{ km.} \\
 z = -1.0865 & & \delta e = - .0177 \quad \pm .0086 \\
 u = -2.6257 & & \delta\omega = -2^\circ 45' \quad \pm 1^\circ 01' \\
 v = +2.8217 & & \delta P = - .00077 \quad \pm 0.0027
 \end{array}$$

The results of the solution giving the values of the elements, with their probable errors, are given in Table III while comparison of the final with the preliminary residuals in Table I shows the improvement effected. The sum of the squares has been reduced from 33.16 to 24.52, while the general run of the observations and their agreement with the final elements is graphically exhibited in the velocity curve accurately drawn to scale.

TABLE III.

Element	Preliminary	Final
U = Period.....	3.2442	3.24343 \pm .00027 days
e = Eccentricity.....	0.04	0.0223 \pm .0086
K = Half amplitude.....	61.5	62.23 \pm 0.46 km.
γ = Velocity of system.....	+0.22	+0.16 \pm 0.29 km.
ω = Longitude of apse.....	0°	357° 55' \pm 1° 01'
T = Time of periastron passage.....	1.549	J. D. 2,421,801.549
a sin i = Projected semi-axis major.....	2,741,000	2,773,000 km.

It may be of interest to point out that, although the spectra are all sufficiently exposed and that on some nights the seeing was poor and clouds interfered, the average time

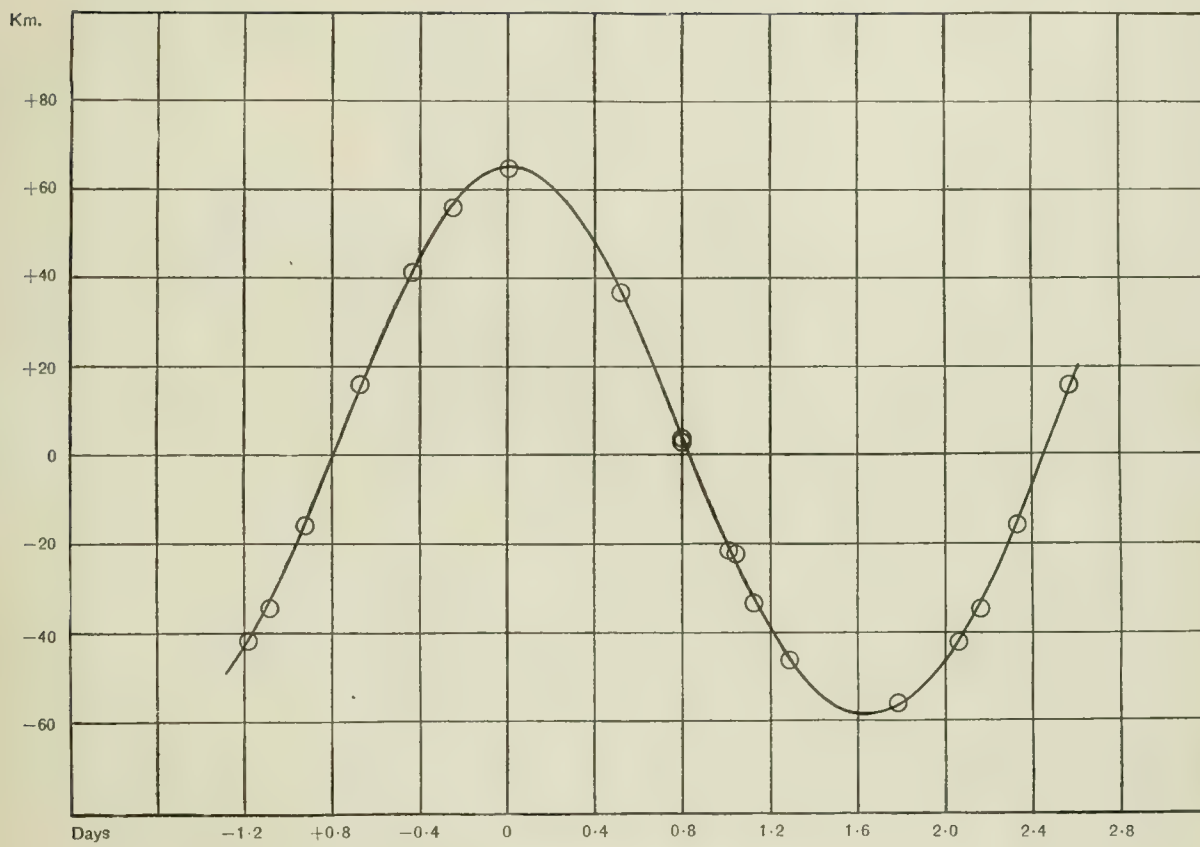
given for this star of 6.96 photographic magnitude was only about 20 minutes. With good silver surfaces and fair seeing, good spectra could be obtained in 15 minutes. This is for a linear dispersion at $H\gamma$, as previously stated, of 35 Å per millimetre, and is an indication not only that the makers have produced optical surfaces of the highest grade, but that temperature difficulties have been so far overcome that excellent figure under observing conditions is maintained, and further, that the "seeing" conditions at Victoria are generally good.

The discussion of the 15 spectra from which this orbit has been obtained gives a good idea of the accuracy of the radial velocity determinations obtainable with the spectrograph. A glance at the column of final residuals show them to be all satisfactorily small considering the low dispersion, the greatest being only slightly over 2 km. per second, the mean 1.07 km. and the probable error of a single plate ± 0.89 km. When it is considered that with three prism spectrographs giving linear dispersion of about 10 Å, three and a half times greater than that used here, the probable error of a single plate is of the order of 0.5 km., we have good reason to be satisfied with the accuracy and to have confidence in the velocity values obtained.

Dominion Astrophysical Observatory,

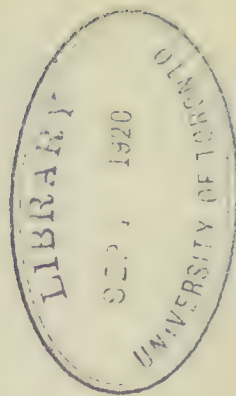
Victoria, B.C.

Feb. 3, 1919.



Velocity Curve of H. R. 8170

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ORBIT OF THE SPECTROSCOPIC BINARY 1 GEMINORUM

BY REYNOLD K. YOUNG

1 Geminorum [α (1900) = $5^h 58^m .0$, $\delta + 23^\circ 16'$, vis. mag. = 4.30, type G5.] was announced as a spectroscopic binary in Lick Obs. Bul. Vol. IV, page 107. Four spectrograms were made at the Lick Observatory from 1903 to 1906. Three additional spectrograms were made at the Bonn Observatory from 1909 to 1912. The star was placed on the observing list at Ottawa in December of 1916 in the hope that the range might prove large enough to permit its orbit being obtained with one prism dispersion. Twenty-six plates were secured in the early months of 1917 but these did not seem sufficient to give accurate elements and it was therefore left to be finished from observations with the 72-inch reflector at Victoria.

The determination of the period has proved to be difficult. Fifty-one observations have been secured here and these are in harmony with a period of 9.590 days. This same period will satisfy the Ottawa observations in 1917 very well and the Bonn observations in 1909 and 1912. The residuals are somewhat larger than one would be led to expect from the fine quality of the spectrum but on the whole they indicate that the period 9.590 days is satisfactory. The Lick observations taken in 1903 to 1906 could not be made to agree and it would seem that there are peculiarities in the orbit not yet explained. The double amplitude of the curve is twenty-three kilometers only and the irregularities in the curve are of the order of five kilometers or a little over so that the complete investigation with one prism dispersion would prove a difficult task. Three prism dispersions would be much better but until such is available the present elements serve as a good approximation to give the general form of the curve.

In the table of observations, which follows, the plates taken at Ottawa were measured with the Toepler measuring machine while the Victoria spectrograms were measured on the Hartmann comparator with a sky or α Bootis standard. Some of the plates were measured with both standards and seemed to give practically the same result.

TABLE OF OBSERVATIONS

Plate	Observer	Date		Julian Day	Velocity	Wt	Phase	O-C
Lick	"	1903	Jan. 4	2,416,119.78	+33.8	.....	0.52	
"	"	1905	Sept. 27	7,116.01	+19.8	.....	1.83	
"	"	1906	Oct. 1	7,485.04	+15.8	.....	6.44	
"	"	"	Nov. 9	7,524.98	+19.9	.....	8.02	
Bonn	"	1909	Jan. 22	8,329.43	+12.3	.....	6.91	-0.9
"	"	"	" 25	8,332.42	+16.9	.....	0.41	-0.7
"	"	1912	Feb. 7	9,440.38	+21.2	.....	5.42	-1.7
Ottawa								
7950	Y	1916	Dec. 17	2,421,215.624	+19.6	1	6.51	+3.4
7989	"	1917	Jan. 12	1,241.632	+35.0	1	3.75	+6.4
7998	"	"	" 16	1,245.683	+ 7.5	1	7.80	+0.3
8013	"	"	" 22	1,251.771	+35.6	1	4.30	+8.3
8014	"	"	" 26	1,255.469	+12.7	1	8.00	+6.5
8027	"	"	Feb. 1	1,261.758	+29.0	1	4.70	+3.0
8044	"	"	" 11	1,271.658	+26.4	1	5.01	+1.4
8045	"	"	" 11	1,271.708	+27.0	1	5.06	+2.2
8049	"	"	" 12	1,272.619	+16.1	1	5.97	-3.9
8052	"	"	" 12	1,272.676	+17.5	1	6.03	-2.0
8061	"	"	" 15	1,275.762	+15.1	1	9.11	+6.1
8063	"	"	" 18	1,278.584	+26.9	1	2.34	-1.7
8064	"	"	" 18	1,278.658	+37.7	1	2.42	+9.0
8071	P	"	" 24	1,284.517	+ 5.3	1	8.28	-0.5
8073	Y	"	" 27	1,287.507	+28.9	1	1.68	+2.3
8082	"	"	Mar. 1	1,289.556	+33.8	1	3.73	+5.2
8098	"	"	" 6	1,294.562	+ 9.0	1	8.73	+2.2
8099	"	"	" 6	1,294.619	+10.4	1	8.79	+3.4
8100	"	"	" 6	1,294.674	+ 8.5	1	8.84	+0.8
8110	"	"	" 13	1,301.508	+14.1	1	6.09	-5.2
8111	"	"	" 13	1,301.561	+14.6	1	6.14	-4.2
8112	"	"	" 15	1,303.528	+ 5.0	1	8.11	-1.0
8116	C	"	" 16	1,304.641	+16.4	1	9.22	+6.4
8138	Y	"	April 8	1,327.528	+29.3	1	3.34	+0.2
8141	"	"	" 10	1,329.526	+18.9	1	5.34	-4.7
8142	"	"	" 10	1,329.580	+16.6	1	5.39	-6.4
Victoria								
778	Y	1918	Oct. 28	2,421,895.967	+23.5	1	5.97	+3.5
823	"	"	" 30	1,897.929	+ 7.7	$\frac{1}{2}$	7.93	+1.1
856	"	"	Nov. 4	1,902.937	+29.4	1	3.35	+0.3
900	"	"	" 20	1,918.894	+13.5	1	0.12	-1.5
901	"	"	" 20	1,918.901	+10.9	1	0.13	-4.1
926	"	"	" 22	1,920.937	+20.9	1	2.17	+2.7
927	"	"	" 22	1,920.951	+30.4	1	2.18	+2.2
988	P	"	" 26	1,924.902	+21.7	1	6.13	+2.9
1024	Y	"	Dec. 10	1,938.912	+23.9	1	0.96	+1.5
1040	"	"	" 14	1,942.925	+28.9	1	4.97	+3.8
1068	"	"	" 16	1,944.846	+10.6	1	6.90	-2.7
1098	"	"	" 20	1,948.822	+25.7	1	1.28	+1.1
1099	"	"	" 20	1,948.828	+24.7	1	1.29	+0.1
1148	P	"	" 29	1,957.834	+20.2	1	0.70	-0.1
1149	"	"	" 29	1,957.843	+19.3	1	0.71	-1.2
1186	"	"	" 31	1,959.785	.....	0	.....	.....

TABLE OF OBSERVATIONS—*Continued.*

Plate	Observer	Date		Julian Day	Velocity	Wt.	Phase	O-C
1203	Y	1919	Jan. 6	2,421,965.822	+4.0	1	8.69	-2.5
1204	"	"	" 6	1,965.829	+5.4	1	8.70	-1.1
1270	"	"	" 10	1,969.803	+27.2	1	3.08	-2.0
1271	"	"	" 10	1,969.811	+30.0	1	3.09	+0.8
1272	"	"	" 10	1,969.819	+26.1	1	3.10	-3.1
1295	P	"	" 19	1,978.782	+26.4	1	2.47	-2.3
1306	Y	"	" 29	1,988.719	+26.6	1	2.82	-2.5
1307	"	"	" 29	1,988.728	+25.8	1	2.83	-3.3
1327	P	"	" 30	1,989.787	+25.2	1	3.89	-3.1
1328	"	"	" 30	1,989.795	+24.6	1	3.90	-3.7
1342	Y	"	" 31	1,990.741	+27.4	1	4.84	+1.8
1343	"	"	" 31	1,990.749	+27.9	1	4.85	+2.3
1369	P	"	Feb. 1	1,991.834	+21.1	1	5.93	+0.9
1381	"	"	" 2	1,992.714	+12.3	1	6.81	-1.7
1382	"	"	" 2	1,992.719	+12.8	1	6.82	-1.2
1391	"	"	" 4	1,994.723	+9.2	1	8.82	+2.1
1395	Y	"	" 5	1,995.584	+13.3	1	0.09	-1.3
1396	"	"	" 5	1,995.592	+10.3	1	0.10	-4.3
1397	"	"	" 5	1,995.601	+12.0	1	0.11	-2.7
1407	"	"	" 5	1,995.800	+13.7	1	0.31	-3.1
1408	"	"	" 5	1,995.811	+12.9	1	0.32	-3.9
1409	"	"	" 5	1,995.820	+13.3	1	0.33	-3.5
1427	"	"	" 11	2,001.772	+17.4	1	6.28	-0.5
1428	"	"	" 11	2,001.778	+17.4	1	6.29	-0.5
1448	P	"	" 16	2,006.735	+25.0	1	1.66	-1.5
1449	"	"	" 16	2,006.742	+26.5	1	1.66	0.0
1477	"	"	" 21	2,011.695	+14.4	1	6.61	-1.0
1491	"	"	" 23	2,013.749	+9.5	1	8.67	+3.0
1492	"	"	" 23	2,013.756	+9.7	1	8.68	+3.2
1516	"	"	Mar. 8	2,026.651	+28.2	1	2.39	-0.5
1559	Y	"	" 19	2,037.626	+25.4	1	3.78	-2.8
1583	P	"	" 20	2,038.675	+26.8	1	4.82	+1.2
1603	Y	"	" 21	2,039.638	+23.3	1	5.79	+2.3
1642	P	"	" 23	2,041.722	+6.2	1	7.87	-0.5
1643	"	"	" 23	2,041.727	+7.8	1	7.88	+1.0
1662	Y	"	" 24	2,042.625	+2.1	1	8.77	-4.7

Both the Ottawa and Victoria measures were used in forming the following normal places.

	Phase from J. D. 2,421,890	Velocity	Wt.	Preliminary O-C	Final O-C	Preliminary p.v.v.	Final p.v.v.
1.....	9.468	+12.3	1.33	-0.60	-0.12	.48	.01
2.....	0.790	+21.1	0.50	-0.05	.00	.00	.00
3.....	1.472	+25.5	0.67	-0.06	-.09	.00	.01
4.....	2.317	+29.8	1.60	+1.14	+1.26	1.30	1.59
5.....	3.163	+28.3	1.16	-1.31	-0.89	2.00	.92
6.....	3.884	+27.4	0.83	-1.63	-0.99	2.22	.84
7.....	4.980	+25.9	1.00	0.00	+0.86	.00	.74
8.....	6.037	+20.4	1.00	+0.20	+0.94	.04	.88
9.....	6.393	+16.4	0.50	-1.30	-0.68	.85	.23
10.....	6.843	+11.9	0.50	-2.32	-1.88	2.69	1.76
11.....	7.968	+7.3	0.67	+0.60	+0.83	.24	.46
12.....	8.722	+6.5	1.50	-0.66	-0.11	.66	.00

From these normal places the preliminary elements were determined graphically.

$$\begin{aligned}
 P &= 9.590 \text{ days} \\
 T &= \text{J. D. } 2,421,898.559 \\
 e &= 0.20 \\
 \omega &= 195^\circ \\
 K &= 11.75 \text{ km.} \\
 \gamma &= +20.13 \text{ km.} \\
 c &= +17.85 \text{ km.}
 \end{aligned}$$

The residuals which the normal places leave when represented by the elements are shown under the heading O-C preliminary in the table of normal places. Observation equations were formed for these residuals and the elements adjusted by the method of least squares. The steps in the solution are recorded below.

OBSERVATION EQUATIONS							Wt.
1.	1.000x	-.615y	-.577z	+.959u	+1.154v	-.600=0	1.33
2.	1.000	+.087	+1.030	+1.012	+.952	-.050	0.50
3.	1.000	+.462	-.388	+.808	+.631	-.060	0.67
4.	1.000	+.726	-.498	+.446	+.280	+1.140	1.00
5.	1.000	+.807	-.962	+.059	+.005	-1.310	1.16
6.	1.000	+.758	-.935	-.259	-.199	-1.630	0.83
7.	1.000	+.491	-.232	-.678	-.503	0.000	1.00
8.	1.000	+.006	+.781	-.928	-.813	+0.200	1.00
9.	1.000	-.207	+1.004	-.948	-.904	-1.300	0.50
10.	1.000	-.503	+1.025	-.899	-.972	-2.320	0.50
11.	1.000	-1.143	-.578	-.262	-.428	+.600	0.67
12.	1.000	-1.104	-.812	+.464	+.590	-.660	1.50

where $x = d\gamma$

$y = dK$

$z = Kde$

$u = Kd\omega$

$v = \frac{-K\mu}{(1-e^2)^{3/2}} dT$

NORMAL EQUATIONS

$$\begin{aligned}
 10.667x & \quad -.446y & \quad -.896z & \quad -.614u & \quad -.902v & \quad -4.811=0 \\
 & +5.504 & \quad -.851 & \quad -.861 & \quad -1.193 & \quad +.392=0 \\
 & & +6.034 & \quad -.583 & \quad -.473 & \quad +.555=0 \\
 & & & +4.978 & \quad +4.903 & \quad +.855=0 \\
 & & & & +5.045 & \quad +.407=0
 \end{aligned}$$

whence $x = -0.4164$

$y = -0.0082$

$z = +0.0762$

$u = -1.6985$

$v = -1.4903$

or $d\gamma = -0.42 \text{ km.}$

$dK = -0.01 \text{ km.}$

$de = +.0065$

$d\omega = +8^\circ.28$

$dT = +0.182 \text{ day.}$

The final elements are

$$P = 9.590 \text{ days}$$

$$e = 0.2065$$

$$\pm .0344$$

$$K = 11.74 \text{ km.}$$

$$\pm .33 \text{ km.}$$

$$\gamma = +19.71 \text{ km.}$$

$$\pm .22 \text{ km.}$$

$$\omega = 203.28$$

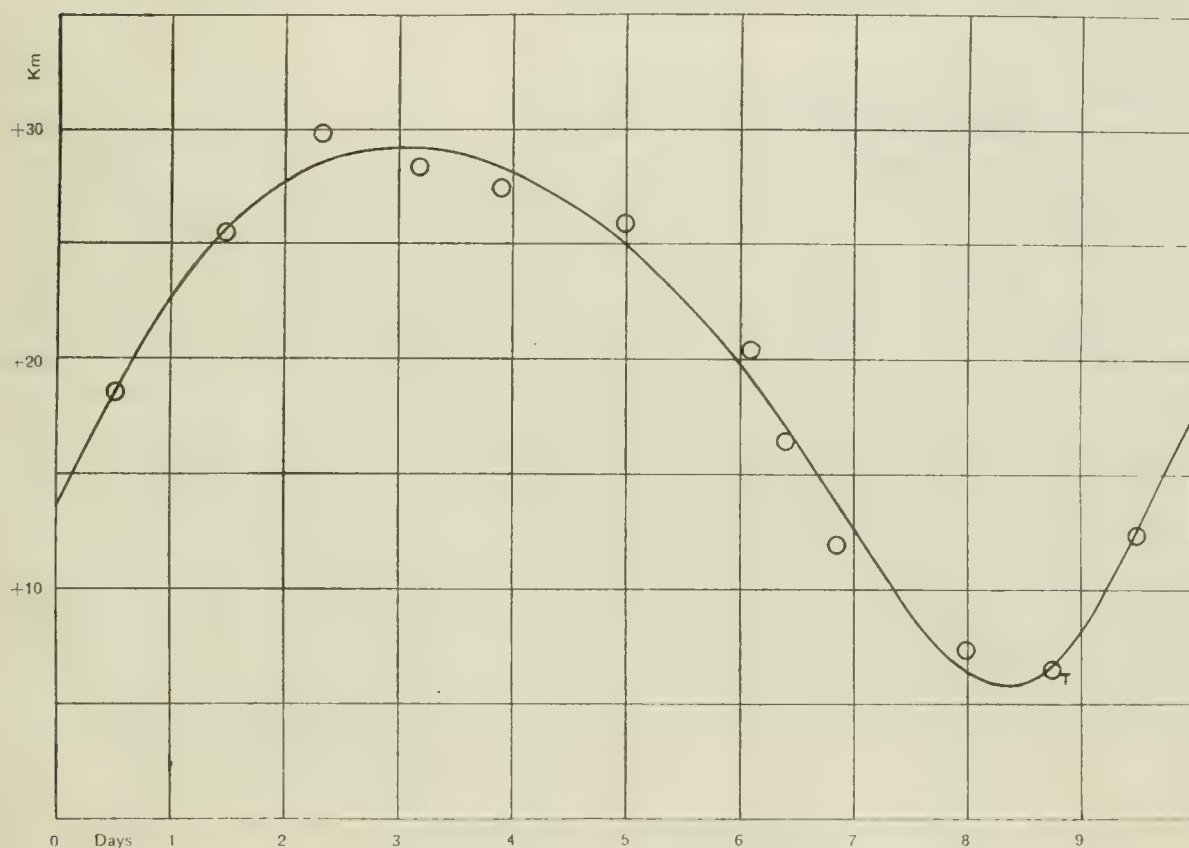
$$\pm 6.80$$

$$T = \text{J. D. } 2,421,898.741$$

$$\pm .196 \text{ day}$$

$$a \sin i = 1,510,000 \text{ km.}$$

$$\frac{m_1^3 \sin^3 i}{(m + m_1)^2} = .0015 \odot$$



These elements are suggestive of the spectroscopic elements for the cepheid variables. The period is the shortest yet found for a star of G type if we exclude the Cepheids but is quite normal for a star of that class. The range is small and the eccentricity high for a binary of such short period. The orbit is minute. The observations do not fit the curve as well as the character of the spectrum would lead one to expect, the probable error of a single plate being, for Victoria, 1.61 km., for Ottawa, 3.00 km. All these characteristics belong also to the Cepheids. On the other hand the star has not been observed to vary and accepting Adams' value for the parallax and luminosity, $\pi = 0.052$, $L = 6.92$ the absolute magnitude is $+2.82$. According to Shapley's curve in the *Astronomical Society of the Pacific*, February, 1918, for the Cepheid variables, a star of this period and apparent

magnitude should have an absolute magnitude of -3.0 . The writer suspected the spectrum to vary somewhat from F8 to G5 or K, but on making estimates of the relative intensities of the pairs of lines used by the Mount Wilson Observatory for the determination of type, this apparent variation vanished and it was further noticed that the altered appearance of the spectrum depended on the exposure of the plates. Those plates that were normal were all alike but the over exposed plates, of which there were several, had the absorption lines so veiled over as to make the spectrum at first glance resemble an earlier type than it really was.

The tentative conclusion one would be led back to is, that the star is probably not a cepheid variable but that it is a G type binary with the shortest period yet found and that the discrepancies in the earlier observations render it advisable to investigate the star further when higher dispersion is available.

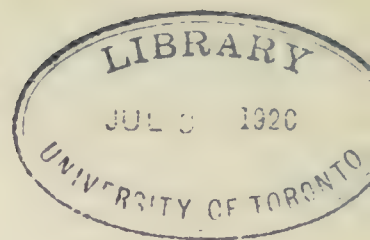
Dominion Astrophysical Observatory,

Victoria, B.C.

July, 1919.

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THE ORBIT OF THE SPECTROSCOPIC BINARY BOSS 4507

BY W. E. HARPER.

This star (1900 $\alpha = 17^h 44^m \cdot 4$, $\delta = +47^\circ 39'$, magnitude 6.34, type Ao) was suspected to be a binary from the large velocity obtained from the first plate made. Though the second plate gave a velocity almost identical with that of the first, yet the third plate, differing by over 30 km from either of the first two, confirmed the binary character of the star. As the range was sufficiently large to warrant proceeding with the determination of its orbit the star was followed quite regularly and the 23 plates, upon which this discussion is based, were obtained within seven weeks of the date of the first spectrogram. The star has been one of the easiest which it has been the writer's experience to investigate and satisfactory elements were obtained with a minimum amount of labour.

The hydrogen lines are much narrower in this spectrum than is generally the case for this type, and they, with the magnesium $\lambda 4481$ and calcium K $\lambda 3933$, are the most intense and best measurable upon the plates. But there are in addition numerous metallic lines which, while not so intense, are nevertheless sufficiently definite for measurement, and the agreement of the results for the different lines is very accordant. While the number of lines measured on each plate varied from 11 to 20, yet all the plates were felt to be dependable and they have been given equal weight in the solution. In the table following the phases have been reckoned from periastron using the final values of P and T. The residuals are computed for each plate.

OBSERVATIONS OF BOSS 4507

Plate Number	Date	Julian Date G. M. T.	Phase	Velocity	Lines	Residual O - C
	1919					
2043	May 28	2,422,107.927	1.214	-85.6	16	+0.6
2056	" 31	110.808	1.271	-86.4	20	-1.3
2120	June 9	119.891	1.881	-28.3	11	+1.2
2133	" 14	124.828	1.170	-89.4	13	-2.8
2139	" 16	126.894	0.412	-20.8	16	-0.7
2152	" 18	128.805	2.323	+23.0	17	+0.5
2165	" 23	133.830	1.699	-53.8	16	-2.4
2186	" 26	136.838	1.883	-30.0	11	-1.9
2195	" 28	138.823	1.044	-86.3	14	-2.0

OBSERVATIONS OF BOSS 4507—*Continued*

Plate Number	Date	Julian Date G. M. T.	Phase	Velocity	Lines	Residual O—C*
2206	June 29	139.830	2.051	— 8.5	12	—2.2
2216	" 30	140.715	0.111	+17.0	12	+0.6
2223	" 30	140.847	0.243	+ 4.5	14	+2.6
2232	July 1	141.749	1.145	—85.4	11	+1.1
2252	" 2	142.800	2.196	+12.7	11	+1.9
2263	" 3	143.765	0.337	— 9.1	14	+1.1
2277	" 6	146.789	0.537	—39.4	13	—2.2
2288	" 7	147.707	1.455	—72.7	17	+2.8
2297	" 7	147.864	1.612	—60.2	13	+1.0
2305	" 8	148.709	2.457	+31.3	13	+0.6
2312	" 8	148.826	2.574	+32.8	13	—0.9
2315	" 8	148.880	2.628	+33.8	14	+0.4
2325	" 9	149.793	0.717	—56.6	19	+2.9
2362	" 14	2,422,154.701	2.800	+24.4	18	—2.9

Thanks to a good run of weather at the time no trouble was experienced in getting the period as the variations could be followed closely. The preliminary value obtained was 2.824 days. When the observations were reduced to one period and plotted, it was seen that while they followed a sine curve approximately, yet there was, without doubt, better agreement when a small eccentricity was used with the longitude of periastron in the first quadrant. Accordingly, provisional elements were adopted as follows.

PRELIMINARY ELEMENTS

Period.....P = 2.824 days
 Eccentricity.....e = 0.02
 Longitude of periastron..... ω = 30°.
 Velocity of system..... γ = —27.24 km.
 Semi-amplitude of range.....K = 60 km.
 Periastron passage.....T = J. D. 2,422,106.732

As no previous observations existed, it was felt desirable to carry through a term for the period in the least-squares solution. The following plates were grouped to form three normal places:—2043 and 2056, 2133 and 2232, 2312 and 2315. These are at maximum and minimum where they have little or no effect on the correction for the period in the solution. All other plates were used separately and thus there were 20 observation equations built up according to the Lehmann-Filhés notation. Owing to the very small

eccentricity it was decided to consider ω as fixed. Making the following transformations:

$$\begin{aligned}x &= \delta \gamma \\y &= \delta K \\z &= K \delta e \\u &= 100 \frac{K}{(1-e^2)^{\frac{3}{2}}} \delta \mu \\&= [3.77841] \delta \mu \\v &= \frac{K}{(1-e^2)^{\frac{3}{2}}} \mu \delta T \\&= [2.12573] \delta T\end{aligned}$$

the observation equations, given equal weight, were as follows:

OBSERVATION EQUATIONS FOR BOSS 4507

1.....	1.000x	+ .309y	- .449z	+ .985u	+ .108v	+0.4=0
2.....	1.000	+ .146	- .720	+1.016	- .061	+2.3
3.....	1.000	- .141	- .986	+1.001	+ .140	+3.7
4.....	1.000	- .519	- .821	+ .843	+ .143	-1.6
5.....	1.000	- .940	+ .447	+ .281	+ .017	+2.7
6.....	1.000	- .982	+ .814	+ .047	000	+1.2
7.....	1.000	- .974	+ .965	- .126	+ .030	+0.3
8.....	1.000	- .814	+ .791	- .535	- .080	-3.4
9.....	1.000	- .582	+ .241	- .772	- .116	-2.0
10.....	1.000	- .426	- .121	- .866	- .009	+1.2
11.....	1.000	- .049	- .784	- .976	+ .127	-1.9
12.....	1.000	- .042	- .792	- .976	- .039	+0.3
13.....	1.000	+ .320	- .993	- .946	- .066	+0.5
14.....	1.000	+ .608	- .741	- .810	- .081	-3.4
15.....	1.000	+ .809	- .267	- .620	+ .025	-1.7
16.....	1.000	+ .958	+ .342	- .349	- .056	-1.0
17.....	1.000	+1.017	+ .848	- .018	- .003	+0.5
18.....	1.000	+ .920	+ .901	+ .446	+ .098	+3.6
19.....	1.000	+ .746	+ .550	+ .712	+ .057	+0.5
20.....	1.000	+ .505	- .036	+ .903	+ .072	-1.4

From these were obtained the normal equations:

$$\begin{aligned}20.000x + .869y - .811z + .760u + .306v + .800 &= 0 \\9.122 - 1.072 + .777 + .079 - .494 & \\9.658 + .557 - .158 + 2.362 & \\10.920 + .643 + 14.120 & \\& .124 + 1.023\end{aligned}$$

resulting in very small corrections to the preliminary values, as follows:

$$\begin{aligned}\delta\gamma &= -.06 \text{ km.} \\ \delta K &= +.15 \text{ km.} \\ \delta e &= -.003 \\ \delta P &= +.00024 \text{ days} \\ \delta T &= -.019 \text{ days}\end{aligned}$$

The final values, then, with their probable errors, are the following.

FINAL ELEMENTS

$$\begin{aligned}
 P &= 2.82424 \text{ days} \pm .00011 \text{ days} \\
 e &= .017 \pm .007 \\
 \omega &= 30^\circ \\
 \gamma &= -27.30 \text{ km} \pm .30 \text{ km.} \\
 K &= 60.15 \text{ km} \pm .47 \text{ km.} \\
 T &= \text{J. D. } 2,422,106.713 \pm .038 \text{ days} \\
 a \sin i &= 2,335,700 \text{ km.} \\
 \frac{m_1^3 \sin^3 i}{(m+m_1)^2} &= 0.06 \odot
 \end{aligned}$$

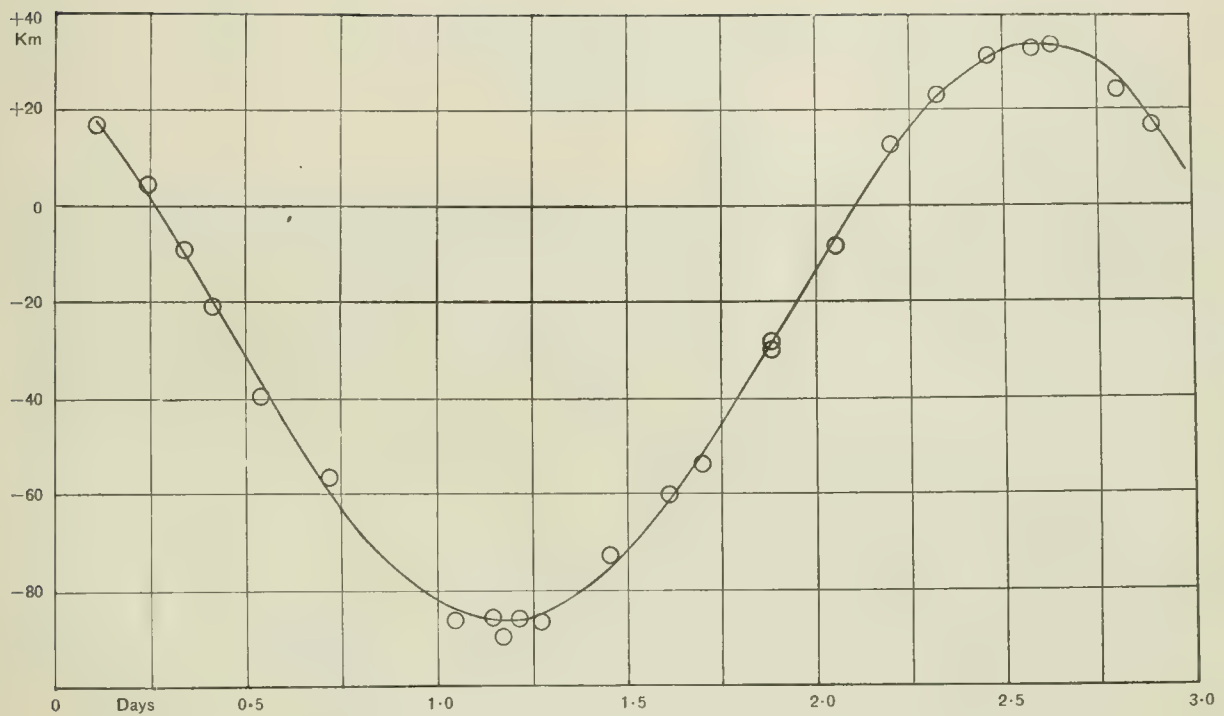
The solution reduced the squares of the residuals about 25 per cent and gave as the probable error of a plate the low value of ± 1.2 km per sec. For single prism work with a dispersion of about 35 angstroms per millimetre and for a spectrum with lines of only moderate sharpness, this is extremely satisfactory and speaks well for the performance of the instrumental equipment. No doubt the long focal length of the telescope, 108 feet, and the consequent complete illumination of the slit, combined with good seeing conditions all contribute to the accuracy of the measures.

The graph shown represents the final elements with the individual observations plotted. All the residuals are under 3 km.

Dominion Astrophysical Observatory,

Victoria, B.C.

July 21, 1919.



Radial Velocity Curve of Boss 4507 showing Individual Observations

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ORBIT OF THE SPECTROSCOPIC BINARY BOSS 4669.

BY REYNOLD K. YOUNG.

The star [α (1900) = $18^h 02.1^m$, $\delta +29^\circ 46'$, vis. mag. 5.71, type A2] was announced as a binary by the Mount Wilson Observatory in the publications of the Astronomical Society of the Pacific, Volume 29, p. 259. It was also independently discovered to have a variable radial velocity from four plates taken with the 72-inch reflector in 1918. Since then we have obtained twenty-seven additional spectrograms as shown in the journal of observations below.

OBSERVATIONS OF BOSS 4669.

Plate	Date	Julian Day	Velocity	No. of Lines	Wt.	Phase from J. D. 2,422,048	O-C
Mt. Wilson	May 25, 1913	2,419,913.959	+ 7			9.435	+1
"	June 16, "	9,935.899	+23			2.539	+4
"	July 11, "	9,960.912	-11			8.328	-4
"	" 2, 1917	2,421,412.913	+ 5			8.917	+8
"	Sept. 5, "	1,477.736	- 9			6.456	+1
Ottawa	" 24, "	1,496.551	- 8.6			6.047	-1.4
"	" 26, "	1,498.557	- 9.8			8.053	-0.4
Mt. Wilson	" 29, "	1,501.646	+42			1.530	+3
Victoria							
227	June 24, 1918	2,421,769.846	+39.4	13	1	0.594	+1.4
321	July 11, "	1,786.831	-10.9	13	1	7.967	-1.4
502	Aug. 27, "	1,833.654	- 9.8	15	1	6.730	-0.8
631	Sept. 20, "	1,857.672	+28.6	8	1	1.912	+1.9
1779	April 8, 1919	2,057.022	- 3.25	18	1	9.022	-1.1
1807	" 14, "	2,063.001	- 4.43	15	1	5.389	+0.1
1832	" 14, "	2,063.983	- 3.41	14	$\frac{1}{2}$	6.371	+4.1
1850	" 21, "	2,070.968	+ 3.18	14	1	3.744	-2.3
1867	" 22, "	2,071.988	+ 0.15	16	1	4.764	+1.5
1913	" 30, "	2,079.001	+22.60	10	1	2.166	-2.6
1928	May 2, "	2,081.977	- 3.77	14	1	5.142	-0.6
1958	" 4, "	2,083.962	- 7.98	17	1	7.127	+1.7
1988	" 6, "	2,085.988	- 0.00	15	1	9.153	+0.1
1994	" 3, "	2,088.848	+19.33	11	1	2.400	-2.0
2011	" 19, "	2,098.916	+17.35	18	1	2.856	+2.7
2026	" 20, "	2,099.934	+ 4.21	17	1	3.874	-0.3
2036	" 22, "	2,101.929	- 7.77	10	1	5.869	-1.2

OBSERVATIONS OF BOSS 4669—*continued*

Plate	Date	Julian Day	Velocity	No. of Lines	Wt.	Phase from J. D. 2,422,048	O—C
<i>Victoria—con.</i>							
2064	June 1, 1919	2,111.870	— 9.14	14	1	6.198	—1.5
2073	" 2, "	2,112.892	— 9.62	19	1	7.220	+0.2
2088	" 3, "	2,113.944	— 8.25	16	1	8.272	—0.7
2098	" 4, "	2,114.908	+ 1.79	15	1	9.236	+0.3
2110	" 6, "	2,116.849	+40.60	15	1	1.565	+2.5
2113	" 6, "	2,116.931	+37.80	14	1	1.647	+1.3
2119	" 9, "	2,119.866	+ 0.41	16	1	4.582	+0.7
2132	" 14, "	2,124.799	+ 8.19	13	1	9.515	—0.3
2148	" 17, "	2,127.886	+14.72	16	1	2.990	+1.6
2176	" 24, "	2,134.803	+23.73	8	1	9.907	—0.2
2180	" 24, "	2,134.902	+27.24	14	1	0.394	—1.5
2349	July 13, "	2,153.806	+15.96	14	1	9.686	+1.7
2365	" 14, "	2,154.746	+46.30	16	1	1.014	—0.9
2376	" 14, "	2,154.911	+45.70	15	1	1.179	—0.3

Two observations taken at Ottawa by Mr. Harper are also available. The early observations, those taken in 1913 and 1917 at Mount Wilson and Ottawa were made use of in determining the period only. The spectrum is particularly well suited for accurate measurement. Numerous lines of Iron and other well known elements such as Calcium, Magnesium, Strontium, Hydrogen, Titanium are present. In general about fifteen of the sharpest lines were selected for measurement. The residuals which result from the comparison of the measurements with the computed values from the final elements are found in the table of observations under the heading O—C'. Considering the dispersion employed (35 A. U. per mm. at H γ) they are satisfactorily small, yielding a probable error for a single plate of 1.0 km.

The computation of the orbital elements presents no serious difficulties. All the observations fit a simple elliptic curve and there is no trouble in connecting the early observations with the more recent ones. The period was found by trial and finally fixed at 9.6120 days. It is not subject to an uncertainty of more than .0004 day. The observations were next grouped into fifteen normal places.

NORMAL PLACES.

	Phase from J. D. 2,422,048	Velocity	Wt.	O—C Preliminary	O—C Final	Σp_2 Preliminary	Σp_2 Final
1.....	0.344	+25.48	2	—1.27	—0.87	1.61	0.76
2.....	0.594	+39.40	1	+1.27	+1.40	0.80	0.98
3.....	1.014	+46.30	1	—0.80	—0.85	0.32	0.36
4.....	1.179	+45.70	1	—0.36	—0.25	0.07	0.03
5.....	1.606	+39.20	2	+1.22	—1.82	1.49	3.31
6.....	2.039	+25.60	2	—3.21	—2.36	10.30	5.57
7.....	2.749	+17.13	3	+0.03	+0.89	0.00	0.79
8.....	3.809	+ 3.70	2	—2.05	—1.41	4.20	1.99
9.....	4.673	+ 0.28	2	+0.70	+1.11	0.49	1.23
10.....	5.265	— 4.10	2	—0.47	—0.14	0.22	0.02
11.....	6.101	— 7.46	2½	—0.36	—0.21	0.16	0.05
12.....	7.026	— 9.13	3	+0.34	+0.33	0.18	0.15
13.....	8.120	— 9.58	2	—0.44	—0.55	0.19	0.30
14.....	9.137	— 0.49	3	—0.26	—0.12	0.11	0.02
15.....	9.600	+12.07	2	+0.31	+0.66	0.10	0.44

The weights in column four indicate the number of plates in a normal place. These were divided by two in forming the observation equations so as to reduce them to an average value near unity. Preliminary elements were determined from the normal places by Dr. King's graphical method. The column head O-C' Preliminary in the table of normal places gives the comparison of the observations with these elements. Σpv^2 is 20.2.

PRELIMINARY ELEMENTS.

$$\begin{aligned}
 P &= 9.6120 \text{ days} \\
 e &= 0.46 \\
 K &= 28.5 \text{ km} \\
 T &= 2,422,048.697 \text{ Julian Day.} \\
 c &= 18.60 \text{ km} \\
 \gamma &= +7.88 \text{ km} \\
 \omega &= 325^\circ
 \end{aligned}$$

The period was not included in the least squares solution. The observation equations are

OBSERVATION EQUATIONS

1.....	1.000x	+0.663y	-0.964z	+1.222u	-1.775	+1.270
2.....	1.000	+1.062	+0.358	+0.992	-1.531	-1.270
3.....	1.000	+1.377	+0.826	+0.269	-0.009	+0.800
4.....	1.000	+1.341	+1.417	-0.003	+0.447	+0.360
5.....	1.000	+1.057	-1.081	-0.469	+0.828	-1.220
6.....	1.000	+0.735	-1.351	-0.670	+0.738	+3.210
7.....	1.000	+0.324	-0.895	-0.735	+0.513	-0.030
8.....	1.000	-0.074	-0.034	-0.629	+0.316	+2.050
9.....	1.000	-0.290	+0.487	-0.481	+0.227	-0.700
10.....	1.000	-0.403	+0.742	-0.362	+0.183	+0.470
11.....	1.000	-0.525	+0.958	-0.168	+0.129	+0.360
12.....	1.000	-0.608	+0.966	+0.090	+0.059	-0.340
13.....	1.000	-0.596	+0.450	+0.494	-0.111	+0.440
14.....	1.000	-0.284	-1.025	+1.014	-0.676	+0.260
15.....	1.000	+0.137	-1.669	+1.235	-1.318	-0.310

$$\begin{aligned}
 \text{where } x &= d\gamma \\
 y &= dK \\
 z &= Kde \\
 u &= Kd\omega
 \end{aligned}$$

$$v = \frac{K\mu}{(1-e^2)^{\frac{3}{2}}} dT.$$

These reduce to the following normal equations.

$$\begin{array}{rcccccc}
 15.250x + 1.610y & -2.352z & +1.311u & -1.453v & -5.440 & = 0 \\
 & 6.307 & -3.509 & -0.022 & -0.160 & +1.534 = 0 \\
 & & 14.432 & -2.446 & +2.834 & -3.653 = 0 \\
 & & & 7.617 & -7.482 & -1.533 = 0 \\
 & & & & 8.694 & +0.832 = 0
 \end{array}$$

whence

$$\begin{array}{ll}
 x = -0.3435 & \text{or } d\gamma = -0.34 \\
 y = -0.0095 & dK = -0.01 \\
 z = +0.2407 & de = +0.0084 \\
 u = +0.7115 & d\omega = +1^{\circ}43 \\
 v = +0.3806 & dT = +0.0143 \text{ day}
 \end{array}$$

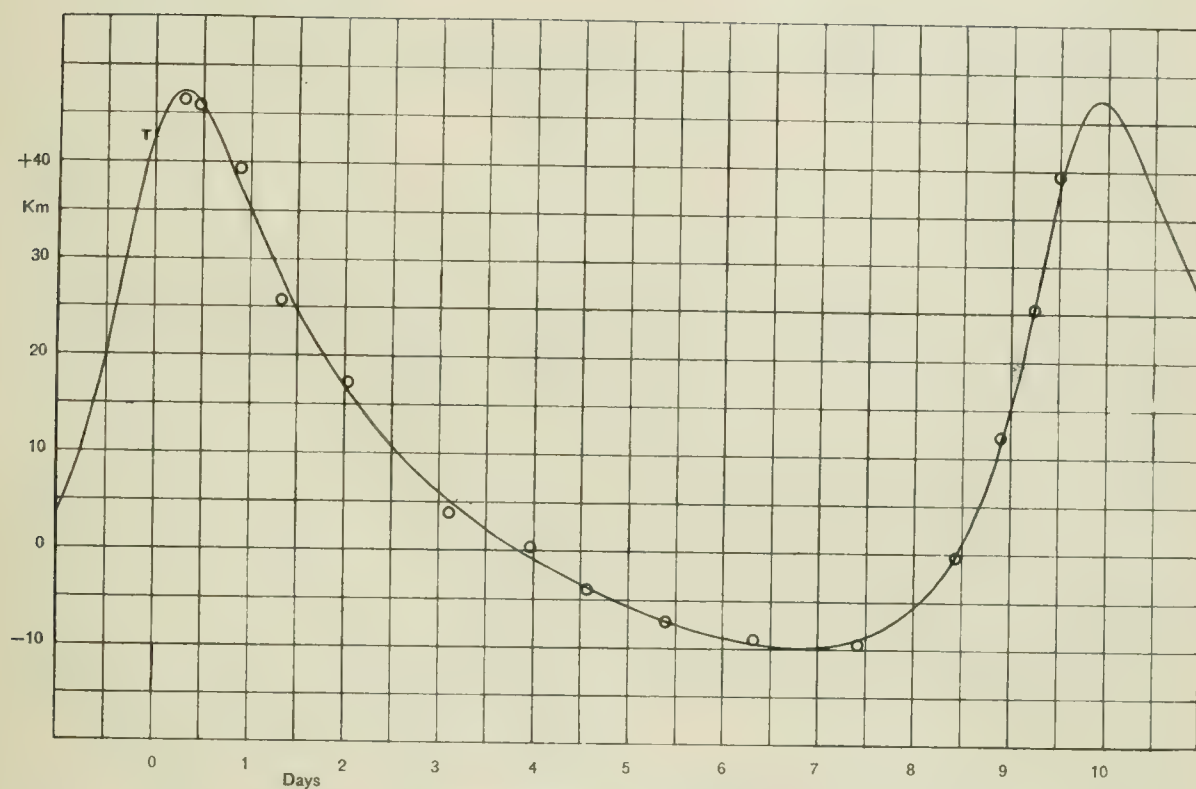
And so the final elements become

FINAL ELEMENTS

$$\begin{array}{ll}
 P = 9.6120 \text{ days} & \pm .0004 \text{ (estimated)} \\
 e = 0.4684 & \pm .0083 \\
 \omega = 326^{\circ}43 & \pm 0^{\circ}85 \\
 T = \text{J. D. } 2,422,048.711 & \pm 0.0110 \text{ day} \\
 \gamma = 7.54 \text{ km.} & \pm 0.23 \text{ km.} \\
 K = 28.49 \text{ km.} & \pm 0.37 \text{ km.} \\
 a \sin i = 3,330,000 \text{ km.} \\
 \frac{m_1^3 \sin^3 i}{(m + m_1)^2} = 0.016 \odot
 \end{array}$$

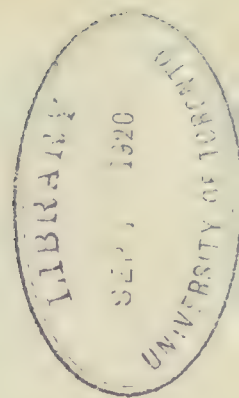
Σpv^2 for these elements is 16.60 as opposed to 20.2 for the preliminary elements. The radial velocity curve is shown in the figure the initial phase, zero days, being counted from periastron.

Dominion Astrophysical Observatory,
 Victoria, B.C.
 July, 1919.



Radial Velocity Curve of Boss 4669

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THE SPECTROSCOPIC ORBITS OF THE ECLIPSING VARIABLES
U OPHIUCHI, RS VULPECULAE, AND TW DRACONIS

BY J. S. PLASKETT

INTRODUCTION

In determining the orbital elements of a spectroscopic binary from a series of measurements of the radial velocity, we can usually obtain the period, the eccentricity of the relative orbit, the maximum orbital velocity, the velocity of the centre of mass of the system, and the longitude and time of periastron.

The inclination of the plane of the orbit to the plane tangent to the celestial sphere is indeterminable and consequently, though formulæ are available giving the semi-axis major and the mass, these both appear as functions of the sine of the inclination, and their actual values must remain unknown so long as the inclination is unknown. Further, in respect to the expression for the mass of the system, it appears as a function of the ratio of the masses of the two bodies and unless this is known, which is the case only in the comparatively few instances when the spectra of both components are present, neither the mass of each nor the total mass of the system, always appearing with the function of the inclination attached, can be determined.

It is only in two special cases that the inclination can be obtained: in visual binaries whose orbital elements have been determined and in eclipsing (Algol) variables of which the light curve is accurately known.

In the case of visual binaries, with the inclination and the relative radial velocities of the two components known, we can evidently obtain the masses, the dimensions of the orbit, and the parallax, but not the diameter and densities of the two stars.

In the other case, the one under consideration, where the spectroscopic binary revolves in a plane so nearly in the line of sight that the stars mutually eclipse one another twice in the period, then, if an accurate light curve is available, not only the inclination but the relative dimensions of the two bodies in terms of the major axis of the system can be determined. When, in addition, both spectra can be measured, complete information can be obtained about the actual diameters, masses, densities, and distance apart of the two bodies. This is of importance in view of the small number of stars for which we have such data.

In the three orbits to be discussed here both spectra have been observed in Υ Ophiuchi and R S Vulpeculae, in which consequently complete dimensions are available. With T W Draconis the second spectrum is invisible and the dimensions in this case must depend upon an assumption as to the ratio of the masses of the two bodies.

U Ophiuchi

The eclipsing variable Υ Ophiuchi (α 17h 11.4m; δ + 1° 19' 1900, vis. mag. 5.7, spectral type B9) was placed under observation for radial velocity on Mar. 19, 1919, and observations were continued until June 4. In all 18 plates were obtained of which 14 were used in determining the spectroscopic elements. The remaining four plates were so near the minimum or zero velocity in the orbit that the doubled lines could not be separated, with the result that their velocities are unreliable and were not used.

The lines of the spectrum are rather wide and are diffuse and faint, lacking in contrast, this latter probably due to the superposition of the continuous spectrum of the one star on the absorption lines of the other. One plate, No. 1983, obtained at principal minimum shows the spectrum with single lines. This spectrum is principally, but not wholly, as it is only a partial eclipse, of the fainter star, and hence gives a truer idea of the character and type. From this spectrum the type should be classed as B5, but is rather abnormal in the breadth of the hydrogen lines. In all 9 double lines have been measured H γ , H δ ; He 4472, 4388, 4144, 4026; C 4267; Mg 4481; Ca, K, 3934. Owing to the lack of contrast and the diffuseness of the lines, the measures are difficult and necessarily not of very high accuracy. In many cases some of the lines of the weaker spectrum could only be recognized and bisected by their showing a faint lightening of the spectrum on each side of the wire. Nevertheless, I believe the measures are reliable, as there is fair interagreement among the values for the different lines, and the general dimensions of the system are substantially correct.

TABLE I—OBSERVATIONS OF Υ OPHIUCHI

Plate Number	Date	Julian Date	Phase	Velocity		No. of Lines	Residuals O-C	
				Brighter	Fainter		Brighter	Fainter
1919								
1745	April 2	2,051.022	0.362	-196.9	+179.3	8	- 9.7	- 9.1
1776	" 7	2,056.974	1.282	+148.4	-222.6	8	-19.2	- 7.3
1805	" 13	2,062.973	0.572	-156.7	+159.3	7	+ 6.0	- 1.2
1808	" 14	2,063.019	0.618	-148.2	+128.8	9	- 4.4	-10.2
1905	" 28	2,077.935	0.438	-174.7	+215.4	8	+16.2	+22.8
1911	" 29	2,078.972	1.475	+139.1	-150.2	8	+24.7	+ 4.5
1938	May 3	2,082.876	0.317	-194.2	+194.2	8	- 9.5	+ 8.6
1952	" 4	2,083.866	1.337	+149.0	-194.8	8	-12.3	+13.3
1983	" 6	2,085.885	0.000		- 26.1	6	+14.6	+14.6
2009	" 19	2,098.884	1.259	+181.7	-216.2	8	+13.4	- 0.1
2053	" 30	2,109.911	0.544	-170.4	+174.3	6	+ 1.6	+ 3.1
2072	June 2	2,112.874	0.152	-118.4	+ 73.7	6	- 7.3	-28.1
2084	" 3	2,113.870	1.148	+155.1	-201.1	8	+ 1.9	- 2.1
2097	" 4	2,114.880	0.481	-187.8	+193.8	6	- 1.3	+ 6.1

In the above table the first three columns give the plate number, the date and Julian date of the observations. The fourth column gives the phase from primary minimum of the photometric orbit computed from the initial phase J. D. 2,418,026.703 with the period 1.6773476 days. The fifth and sixth columns give the observed velocities and the eighth and ninth the residuals from the final orbit of the brighter and fainter components respectively, while the seventh column contains the number of doubled lines measured on each plate, with the exception of plate 1983, on which six single lines were measured.

As the photometric orbit does not show any ellipticity and as the observations seem to follow sine curves as closely as can be expected, the orbit was assumed to be circular and consequently only K , the half amplitude and γ the velocity of the system, remain to be determined. From smooth curves drawn through the observations K_b was assumed 182.0 km., K_f 210.0 km. and γ -12.0 km.

The velocity at any phase θ is given by $V = \gamma + K \sin \theta$ and to apply least squares corrections we have $\delta V = \delta \gamma + \delta K \sin \theta$. An ephemeris and observation equations were formed, resulting in the normal equations

$$\begin{aligned} 26.0 \delta \gamma - 2.361 \delta K_b + 2.361 \delta K_f - 5.7 &= 0 \\ 10.424 \delta K_b &+ 24.38 = 0 \\ 10.424 \delta K_f + 55.09 &= 0 \end{aligned}$$

whose solution gave

$$\delta \gamma = +0.5 \qquad \delta K_b = -2.2 \qquad \delta K_f = -5.4$$

and the final elements

$$\begin{aligned} K_b &= 179.8 \pm 2.70 \text{ km.} \\ K_f &= 204.6 \pm 2.70 \text{ km.} \\ \gamma &= -11.5 \pm 1.88 \text{ km.} \end{aligned}$$

while the probable error of a single plate for each spectrum was the same and equal to ± 8.3 km. Considering the character of the spectrum and the difficulty of measurement these results are satisfactory, the uncertainty of K and consequently of the dimensions of the system being only slightly over one per cent.

Applying these values by the well-known formulæ, we have

$$\begin{aligned} a_b \sin i &= 4,147,000 \text{ km.} \\ a_f \sin i &= 4,718,000 \text{ km.} \\ (m_b + m_f) \sin^3 i &= 9.890 \odot \end{aligned}$$

In Shapley's photometric orbit* three solutions are obtained, two assuming uniformly illuminated discs and a third postulating darkening towards the limb. Shapley's second and third solutions are applied here, one uniform, one darkened. These give inclinations of $85^\circ 42'$ and $83^\circ 58'$ respectively, and make the radius of each star 0.252 of the semi axis of the relative orbit in each solution. The dimensions, masses, and densities of the system at once follow.

*Contributions from the Princeton Observatory No. 3, p. 84.

U Ophiuchi whose apparent magnitude is 6.35, is -0.19 , and hence the parallax is $0''.0049$.

A graph showing the sine curves for the two components with the velocities represented by open circles is shown in Fig. 1.

R S Vulpeculæ

The eclipsing variable *R S Vulpeculæ* (α 19h 13.4m, $\delta +22^\circ 16'$, 1900, type A, vis. mag. 7.30) was placed under observation April 26, 1919, and the last plate used in the principal orbit was obtained on July 20, 1919. A fine grained Seed 23 plate was obtained on July 30 and used for the second spectrum. Fourteen plates were obtained in this interval, all of which have been measured and used. The spectrum is of type B8 instead of A, and the magnitude as judged by comparison with U Coronæ and T W Draconis appears considerably brighter than given by Nijland and Stewart.

This binary is especially interesting on account of the great disparity in size of the two components, the fainter star being five times the diameter of the brighter and nine-tenths as bright. It would consequently be expected, when the two stars are of nearly equal brightness, that the second spectrum would be plainly visible, but it can only be seen and measured with great difficulty, and it is estimated to be of only about one-fourth the intensity of the brighter spectrum. Nevertheless, it was measured on six plates, and although the residuals are in some cases rather large, the probable error of the measures of the second spectrum on a single plate being ± 8.1 km., the lines and plates are in fair interagreement. Consequently, there can be no doubt of the reality of the second spectrum, even though the mass of the fainter body is only 0.31 that of the brighter, a greater difference in masses when both spectra appear than has previously been found. Why the second spectrum should be so relatively faint when the two stars are of nearly equal brightness is not apparent. It may be that, although the continuous part of the spectra are of nearly equal intensity, the absorption lines of the second body are fainter than those of the primary rendering them difficult to see when the continuous spectrum of the primary is superposed. Or, again, a more likely explanation is that the lines are widened so much by the rotation of the large diameter faint star as to be made relatively very faint. One plate was made about 2.2 hours after primary minimum, which, according to Stewart's orbit*, would be about an hour after the total phase, so that although it would receive most of the light from the fainter component, about one-fifth would come from the brighter. This spectrum has much the same character as the others, except that the lines are much weaker and thus is in agreement with the above hypothesis. Further an additional plate was obtained on July 30 on Seed 23 emulsion and the finer grain enables the second spectrum to be more readily and certainly measured. On this plate the enhanced line 4549 is plainly doubled, the intensity of the second spectrum being relatively much stronger than in the other lines. Further, the silicon pair 4128, 4131 show fairly strong companions, while the second spectrum in the hydrogen and helium lines is very weak. This would make it appear as if the faint diffuse companion were of Type B9 with relatively weak hydrogen and helium lines, while the bright dense star is B8 or even earlier. The relative intensities of the doubled lines 4549, 4131, 4128 are more nearly

*Astrophysical Journal, 42, 315, 1915.

equal being only about one-half as compared with one-fourth for the hydrogen and helium lines.

Altogether 11 lines have been measured in the primary spectrum, $H\gamma$, $H\delta$; He 4472, 4388, 4144, 4121, 4026; Fe-Ti 4549; Mg 4481; C 4267; Ca, K, 3934 and in the fine grained plate Si 4128, 4131. The lines are of only fair quality for measurement, although much better defined than in U Ophiuchi, but the measures nevertheless are satisfactorily accordant, the probable error of measures of the primary spectrum on a plate being only ± 1.8 km. per second.

In the table of observations given below column 1 contains the plate number, columns 2, 3, date and Julian date of the observation, and column 4 the phase from primary minimum computed from the original phase 2,419,652.963 with a period of 4.477325 days from Stewart's photometric orbit.* Columns 5, 6 contain the velocities of the primary and secondary stars, and columns 8, 9 the residuals in the sense observed minus computed from the final orbit. Column 7 contains the number of lines measured in the primary, and where a second figure is present the number in the secondary spectrum.

TABLE II—OBSERVATIONS OF R S VULPECULAE

Plate Number	Date	Julian Date	Phase	Velocity		No. of Lines	Residuals O-C	
				Brighter	Fainter		Brighter	Fainter
1919								
1888	April 26.....	2,075.981	0.786	-68.3	+132.0	9 10	-2.30	+13.2
1912	" 29.....	078.988	3.793	+22.2		11	-1.28	
1987	May 6.....	085.969	1.818	-63.2	+107.4	8 4	-3.20	+ 7.8
2243	July 1.....	141.903	4.024	+11.2		10	-2.11	
2269	" 3.....	143.903	1.547	-70.7	+131.9	9 7	+2.98	-11.5
2298	" 7.....	147.883	1.050	-76.9	+160.8	9 8	-0.99	+10.3
2316	" 8.....	148.902	2.069	-39.1		7	+2.36	
2329	" 9.....	149.870	3.037	+27.5	-163.7	6 3	+1.96	-10.3
2350	" 13.....	153.818	2.507	- 7.5		10	-2.27	
2367	" 14.....	154.773	3.461	+28.2		7	-2.79	
2390	" 15.....	155.878	0.090	-22.9		6	-1.91	
2428	" 18.....	158.897	3.109	+29.8		10	+2.07	
2441	" 19.....	159.892	4.104	+14.1		9	+5.08	
2449	" 20.....	160.727	0.462	11.4		6	+2.56	
2579	" 30.....	170.760	1.540	-67.2	+132.2	9 8		-11.6

When these velocities and phases were plotted on cross section paper, it was at once seen that the orbit was not circular, although the photometric orbit does not show eccentricity, but this element can only rarely be obtained with accuracy from the photometric observations. Preliminary elements obtained graphically were assumed as follows

e	eccentricity.....	0.05
K	half amplitude velocity.....	54.0 km.
γ	velocity of system.....	-22.65 km.
ω	longitude of apse.....	240°
T	time of periastron.....	1.903 days from minimum.

*Astrophysical Journal, 42, 515, 1915.

An ephemeris and observation equations calculated by means of Lehman-Filhés differential coefficients were computed for applying least squares corrections to e , K , γ and ω . Owing to the smallness of the eccentricity it was considered useless to apply corrections for both ω and T and the latter was considered fixed. The observation equations are given in the following table, where x , y , z , u have the values

$$\begin{aligned}x &= \delta\gamma \\y &= \delta K \\z &= K\delta e \\u &= K\delta\omega\end{aligned}$$

TABLE III—OBSERVATION EQUATIONS RS VULPECULAE

1.....	1.000x	- .288y	+ .004z	+ 1.008u	+ 0.91 = 0
2.....	1.000	+ .366	+ .996	+ .964	+ 4.63
3.....	1.000	+ .895	+ .279	+ .436	- 1.83
4.....	1.000	+ .929	+ .082	+ .342	- 2.27
5.....	1.000	+ .960	- .758	- .127	+ 1.02
6.....	1.000	+ .799	- .978	- .523	- 1.71
5.....	1.000	+ .598	- .728	- .738	- 1.53
8.....	1.000	+ .576	- .579	- .798	- 8.89
9.....	1.000	- .045	+ .514	- .956	- 2.17
10.....	1.000	- .511	+ .984	- .830	- 5.86
11.....	1.000	- .838	+ .658	- .538	+ 0.37
12.....	1.000	- .995	- .029	- .199	+ 0.52
13.....	1.000	- .904	- 1.010	+ .519	- 0.78
14.....	1.000	- .635	- .715	+ .836	+ 6.25

From these observation equations the following normals were obtained:

$$\begin{aligned}14.000x + 0.847y - 1.279z - 0.606u - 11.34 &= 0 \\7.240 - 1.234 - 0.506 - 9.202 &= 0 \\6.670 - 0.058 + 0.744 &= 0 \\6.624 + 24.250 &= 0\end{aligned}$$

Their solution gave

$$\begin{aligned}x &= +0.61 & \delta\gamma &= +0.61 & \pm 0.56 \\y &= +0.98 & \delta K &= +0.98 & \pm 0.79 \\z &= +0.157 & \delta e &= +0.0029 & \pm .0149 \\u &= -3.530 & \delta\omega &= -3.74 & \pm 0.84\end{aligned}$$

whence the final elements

$$\begin{aligned}e &= 0.053 \pm .015 \\K_b &= 54.98 \pm 0.79 & K_f &= 175.9 \\ \gamma &= -22.04 \pm 0.56 \\ \omega &= 236.26^\circ \pm 0.84^\circ \\ T &= 1.903 \text{ days}\end{aligned}$$

The probable error of a single plate for the bright star is ± 1.8 km, and for the faint ± 8.1 km per second. A graph of the orbit with the observations of the principal spectrum represented by circles is shown in Fig. 2.

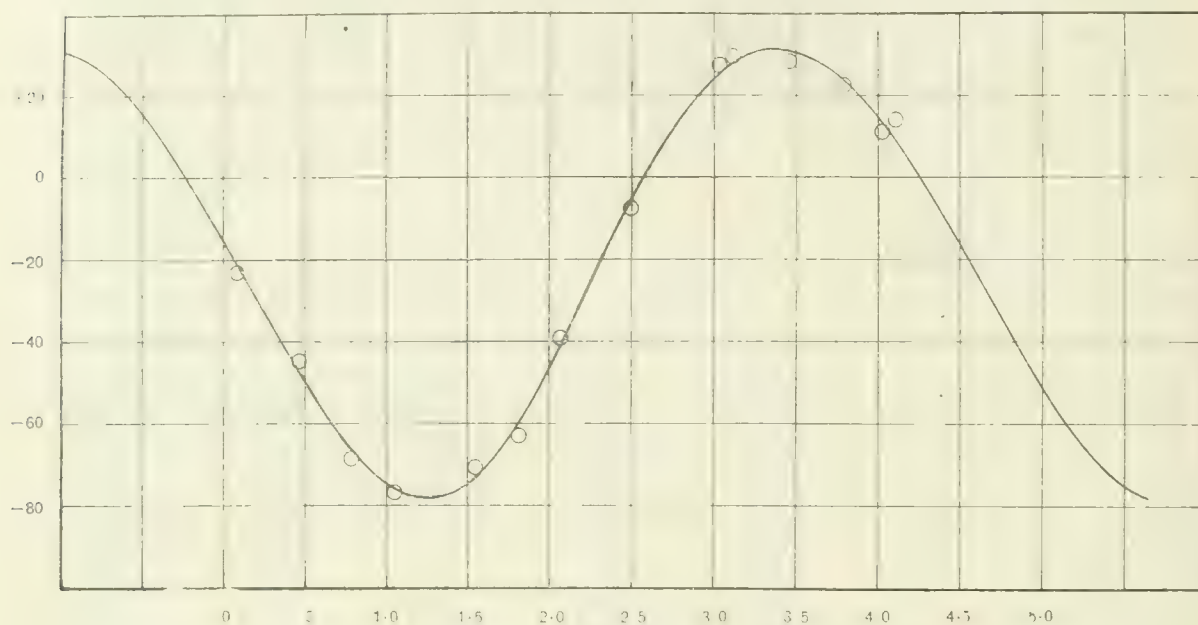


Fig. 2. RS Vulpecula

Applying the above values we obtain by the well known formulæ

$$a_b \sin i = 3,388,000 \text{ km.}$$

$$a_f \sin i = 10,842,000 \text{ km.}$$

$$(m_1 + m_2) \sin^3 i = 5.70$$

Stewart's photometric orbit* gives two solutions, a uniform, and a darkened. The uniform gives a value of the inclination $69^\circ 45'$, radius brighter star $\cdot 090$, radius fainter star $\cdot 450$, while the darkened solution gives $68^\circ 25'$, $\cdot 0932$, $\cdot 466$ for these three quantities. The dimensions, masses and densities in the orbit follow. For comparisons the dimensions from Shapley's darkened orbit† are also given and it appears that further photometric work on this star is desirable.

	Uniform	Darkened	Shapley
a semi-axis relative orbit.	15,190,000	15,300,000	14,230,000
a_b " orbit brighter star	3,610,000	3,644,000	3,389,000
a in terms of sun's radius,	21.84	22.00	20.47
" " " "	5.19	5.24	4.88
r radius brighter star.	1.96	2.05	1.80
" " faint " "	9.81	10.25	5.16
m mass brighter " "	5.26	5.40	4.34
m_b " fainter " "	1.64	1.69	1.36
M total mass	6.90	7.09	5.70
ρ density brighter star	0.70	0.63	0.74
ρ_b " fainter " "	0.0017	0.0016	0.008

*Astrophysical Journal 42, 315, 1915.

†Contributions from Princeton Observatory, No. 3, p. 90.

If we assume the surface intensity of a B8 star to be -2.2^* magnitudes and the sun's absolute magnitude to be 4.86 the absolute magnitude of the brighter component of R S Vulpeculæ, with apparent magnitude 7.75, is $+1.09$ and the parallax is $0''.0046$.

T W Draconis

The eclipsing variable T W Draconis (α 15h 32.4m., $\delta +64^\circ 14'$, 1900; vis. mag. 7.45; spectral type B9) was first observed on April 13, 1919, and the last plate obtained on July 17. During this interval 14 plates were obtained, all of which are used in the orbit. They are not so well distributed as in R S Vulpeculæ, owing to the depth of primary minimum, when the star falls to 9.8 magnitude, making it impracticable to obtain plates at this epoch. The comparative faintness of the secondary, its light being 0.115 of the system, of course renders its spectrum unobservable.

The spectrum classed as B9 is in reality A3 judging by the relative strength of hydrogen and K and the number and intensity of the metallic lines, and in consequence should be capable of accurate measurement. Although the interagreement among the lines is fairly good, the velocities of the plates are disappointing, the residuals unexpectedly high, resulting in a plate error of ± 2.6 km per second. This is probably due to the rather wide and diffuse character of the metallic lines, making the settings uncertain. That the lines are wide should not be a cause for surprise when we consider the nearness of the two bodies and the probable rapid rotation of the bright body in the period of the system.

The data of the observations are given in Table IV, where column 1 contains the number of the plate, columns 2 and 3 the date and Julian date of the observation. Column 4 contains the phase from primary minimum computed from initial photometric phase 2,418,906.453 with period 2.80654 days and column 5 the velocity determined from measures of the number of lines in column 6. Column 7 contains the residuals in the sense observed minus computed from the final orbit.

TABLE IV—OBSERVATIONS OF T W DRACONIS

Plate Number	Date	Julian Date	Phase	Velocity	No. of Lines	Residuals O-C
1919						
1802	April 13	2,422,062.890	1.886	+50.8	12	-2.33
1883	" 26	075.862	0.825	-63.2	20	-0.76
1909	" 29	078.922	1.078	-38.7	17	+3.99
1936	May 3	082.840	2.190	+62.2	12	-3.19
1982	" 6	085.865	2.408	+51.4	12	-4.47
2217	June 30	140.734	1.147	-37.3	17	-2.16
2233	July 1	141.721	2.134	+67.6	11	+2.40
2247	" 2	142.716	0.322	-47.9	7	-2.74
2275	" 6	146.733	1.532	+18.6	13	+4.53
2289	" 7	147.726	2.525	+50.3	11	+6.13
2306	" 8	148.726	0.719	-61.4	14	+4.37
2363	" 14	154.718	1.098	-48.1	15	-7.44
2383	" 15	155.722	2.102	+65.1	9	+0.45
2398	" 17	157.717	1.290	-16.4	11	+1.29

*Astrophysical Journal 40, 415, 1914.

When these observations were plotted it was at once seen that by making the orbit slightly eccentric better agreement could be obtained than with a circular orbit. Although no eccentricity is given by Shapley's orbit,* it is probable that Nijland's observations are not of sufficient accuracy to determine this, and alternative solutions for eccentric and circular orbits gave considerably lower residuals for the former. Preliminary elements which were obtained graphically are as follows.

Period from photometric orbit.....	2.80654 days
Eccentricity e	0.04
Semi-amplitude K	64.5 km.
Velocity of system γ	-0.5 km.
Longitude of apse ω	90°
Time of periastron T	0.020 days

Owing to the smallness of the eccentricity it was considered useless to apply least squares corrections to both T and ω and, in this case, as the latter seemed better determined by the graphical elements, a correction for T was used. The differential coefficients obtained by Lehman-Filhés were used in computing an ephemeris and observation equations which are given in Table V.

TABLE V OBSERVATION EQUATIONS OF TW DRACONIS

1.....1.000x	- .666y	-1.010z	+ .792u	+ 4.47=0
2.....1.000	- .997	+ .147	- .073	- 3.43
3.....1.000	- .953	+ .576	- .296	+ 1.24
4.....1.000	- .659	+ .978	- .708	- 4.29
5.....1.000	- .626	+ .963	- .732	+ 7.22
6.....1.000	- .543	+ .899	- .784	+ 1.78
7.....1.000	- .272	+ .515	- .889	- 1.68
8.....1.000	+ .223	- .427	- .901	- 4.72
9.....1.000	+ .824	- .925	- .541	+ 1.86
10.....1.000	+ .991	- .258	- .129	- 1.65
11.....1.000	+ .998	- .119	- .059	- 3.72
12.....1.000	+ .998	+ .132	+ .066	+ 1.66
13.....1.000	+ .843	+ .918	+ .560	+ 2.49
14.....1.000	+ .665	+1.010	+ .793	- 7.93

where $x = \delta\gamma$

$y = \delta K$

$z = K \delta e$

$u = \frac{K\mu}{(1-e^2)^{3/2}} \delta T$

The normal equations from these observations are

$$\begin{aligned}
 14.000x + .826y + 3.399z - 2.901u - 6.70 &= 0 \\
 8.397 &- 1.554 + 1.652 - 9.327 = 0 \\
 7.329 &- 1.292 - 5.153 = 0 \\
 5.234 &+ .168 = 0
 \end{aligned}$$

*Contributions from Princeton Observatory, No. 3, p. 90

Their solution gives

$$\begin{array}{ll}
 x = + \cdot 1631 & \text{or} \quad \delta\gamma = +0 \cdot 16 \text{ km.} \\
 y = +1 \cdot 2825 & \delta K = +1 \cdot 28 \text{ km.} \\
 z = + \cdot 8766 & \delta e = + \cdot 0136 \\
 u = - \cdot 1298 & \delta T = - \cdot 001
 \end{array}$$

and the final elements

$$\begin{array}{ll}
 e \text{ eccentricity} & \cdot 0536 \pm \cdot 0187 \\
 K \text{ semi amplitude} & 65 \cdot 78 \pm 1 \cdot 13 \\
 \gamma \text{ velocity system} & -0 \cdot 34 \pm 0 \cdot 91 \\
 T \text{ time of periastron} & 0 \cdot 019 \pm \cdot 010 \\
 \omega \text{ longitude of apse} & 90^\circ \\
 a_b \sin^3 i \text{ semi axis major} & = [6 \cdot 40395] = 2,535,000 \text{ km.} \\
 \frac{m_b^3 \sin^3 i}{(m_b + m_t)^2} & = [8 \cdot 91696] = \cdot 0826 \odot
 \end{array}$$

This function of the masses, all that can be determined when the second spectrum cannot be seen, does not give us information in regard to the dimensions or masses of the system. From the photometric orbit we obtain the diameters of the individual stars in terms of the relative orbit, but the latter cannot be known without the ratio of the masses. As a first approximation Shapley assumed the masses equal and later used an empirical formula* for determining the masses of the components. This formula based on the relative light of the two bodies, has its constants determined from spectroscopic binaries in which both spectra show and the ratio of the masses are known. Using this formula $\mu_b = 0 \cdot 4 + 1 \cdot 2 L_b$ the ratio comes as brighter star 0·73 fainter star 0·27 total mass. If we use R S Vulpeculæ as an analogy where the system is somewhat similar, a dense bright small primary with a tenuous, large companion, it seems probable that the ratio of the masses assumed above is certainly not too great. With R S Vulpeculæ where the light of the brighter star is 0·526 of the system, the ratio of the masses is 3·20 while with T W Draconis, where the light of the brighter star is 0·885 of the system, it would certainly seem likely the ratio of masses would be greater. Nevertheless, the ratio given by the formula has been used, and I think may be safely considered as giving minimum dimensions to the orbit, but of course these dimensions depend upon this assumption and cannot be considered absolute, as in the two previous orbits. Using Shapley's two solutions, uniform and darkened, the inclinations are $75^\circ 53'$ and $79^\circ 48'$, while the semidiameters of brighter and fainter are $\cdot 130$ and $\cdot 371$ for the uniform and $\cdot 180$ and $\cdot 334$ for the darkened.

*Contributions from the Princeton Observatory No. 3, p. 123.

The dimensions of the system hence become

	Uniform	Darkened
a_b semi axis major primary orbit.	2,614,000	2,575,000
a_i " " secondary "	7,067,000	6,963,000
a " " relative "	9,681,000	9,538,000
a in terms of radius of sun.	13.92	13.71
a " " " " " " " "	3.76	3.70
r semi diam. brighter	1.81	2.47
r_f " " fainter "	5.10	4.58
mass brighter star..	3.36	3.21
mass fainter " "	1.24	1.19
total mass system.....	4.60	4.40
density brighter star.	.57	.21
" " fainter " "	.0094	.0124

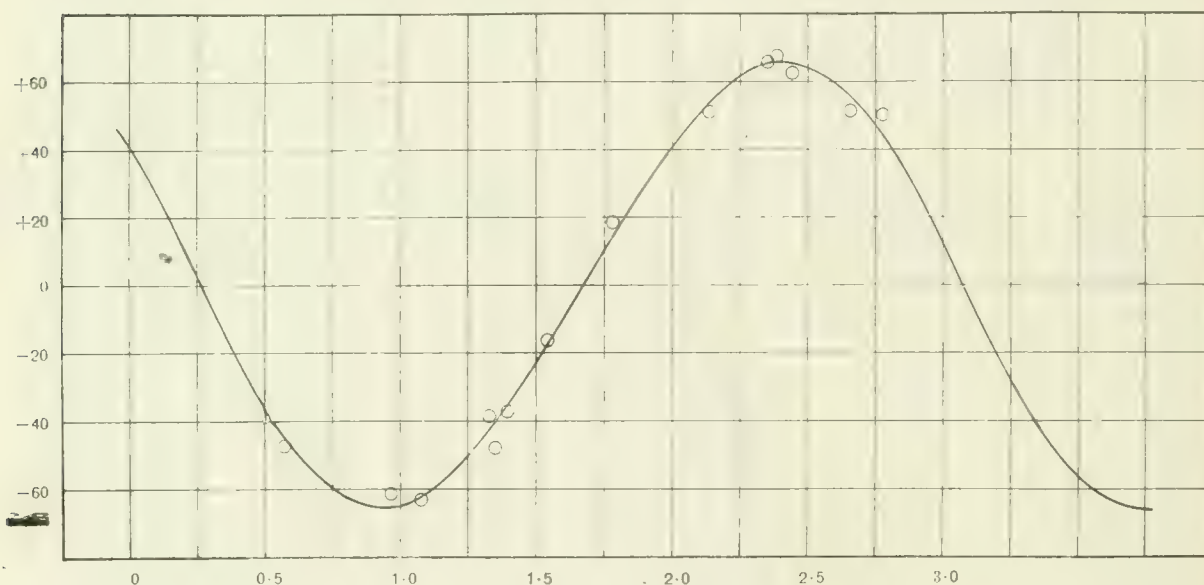


Fig. 3. T W Draconis

A graph of the velocity curve with the observations as circles is shown in Fig. 3.

CONCLUSION.

It may be of interest to summarize the dimensions of the two systems obtained here with the seven previously secured, that are known to me. The orbit of T W Draconis is not included in this summary, as owing to absence of the second spectrum the dimensions are not absolute. The following table gives the principal dimensions using the darkened photometric orbit in each case, where there are two or more solutions.

TABLE VI—ABSOLUTE DIMENSIONS ECLIPSING VARIABLES.

Star	Greatest Radii		Masses		Densities		Distance of Centres.
	r_b	r_t	m_b	m_t	ρ_b	ρ_t	
β Aurigae ¹	2.81	2.81	2.40	2.36	0.11	0.11	17.7
U Herculis ¹	4.56	5.35	7.66	2.93	0.095	0.022	14.8
V Puppis ¹	8.45	7.70	19.4	19.4	0.042	0.055	12.7
B Lyrae ¹	16.2	40.6	1.42	14.2	0.0006	0.0004	59.9
RX Herculis ²	1.54	1.38	0.89	0.89	0.25	0.34	7.5
W Ursae Majoris ³	0.78	0.78	0.69	0.49	2.8	1.9	2.2
Z Herculis ⁴	1.77	3.29	1.6	1.3	0.3	0.04	15.1
U Ophiuchi.....	3.23	3.23	5.36	4.71	0.18	0.16	12.8
R S Vulpeculae.....	2.05	10.25	5.40	1.69	0.63	0.0016	22.0

The above table is self explanatory if it is stated that the linear dimensions are in terms of the sun's radius and the masses and densities in terms of the mass and density of the sun. Fig. 4 gives a graphical representation of the dimensions of the systems of U Ophiuchi and R S Vulpeculae and of the assumed dimensions of T W Draconis in terms of the sun. The intersections of the vertical and horizontal dotted lines represent the centers of mass of the systems. The series of figures to the left are the systems at primary eclipse and those to the right, a quarter revolution away, when at maximum separation. No attempt has been made to represent the stars as elliptical in form in this figure.

There is one other point in connection with these orbits, the coincidence or otherwise of the photometric and spectroscopic phases. Dr. Schlesinger has found in Algol, δ Librae and U Herculis that the phase of mean primary eclipse comes slightly later, about an hour or so, than the time when $u=90^\circ$ in the spectroscopic orbit, while it is evident the two should coincide. No explanation is offered for this discrepancy and it will be of interest to compare the results for the three variables discussed here.

In U Ophiuchi no attempt was made to apply a correction for θ , the phase in the circular orbit, owing to the high probable error and to the fact that nearly all the observations were near their maximum velocity, where they would have little weight in the determination of this correction.

In R S Vulpeculae the velocity curve shows that the spectroscopic phase is considerably later than the photometric and, if the time when $u=90^\circ$ is computed, it is found to be $+0.128 \pm 0.010$ days. In T W Draconis $\omega=90^\circ$, therefore the time when $u=90^\circ$ is the time T found in the orbit, or $+0.019 \pm 0.010$ days. In both these cases, therefore, the spectroscopic phase is later than the photometric by about 3 hours in R S Vulpeculae and 27 minutes in T W Draconis, in the opposite direction to that found by Schlesinger.

¹ Astrophysical Journal 38, p. 169.

² " " 40, p. 399.

³ " " 49, p. 189.

⁴ " " 49, p. 192.

It is hard to imagine any physical cause which would account for a difference in phase in one direction in some instances and in the opposite direction in others. and though the differences appear to be considerably too great to be explained by errors of observation in either the spectroscopic or the photometric orbits, there seems to be no other alternative until more data are available.

Dominion Astrophysical Observatory,
Victoria, B.C.

August 6, 1919.

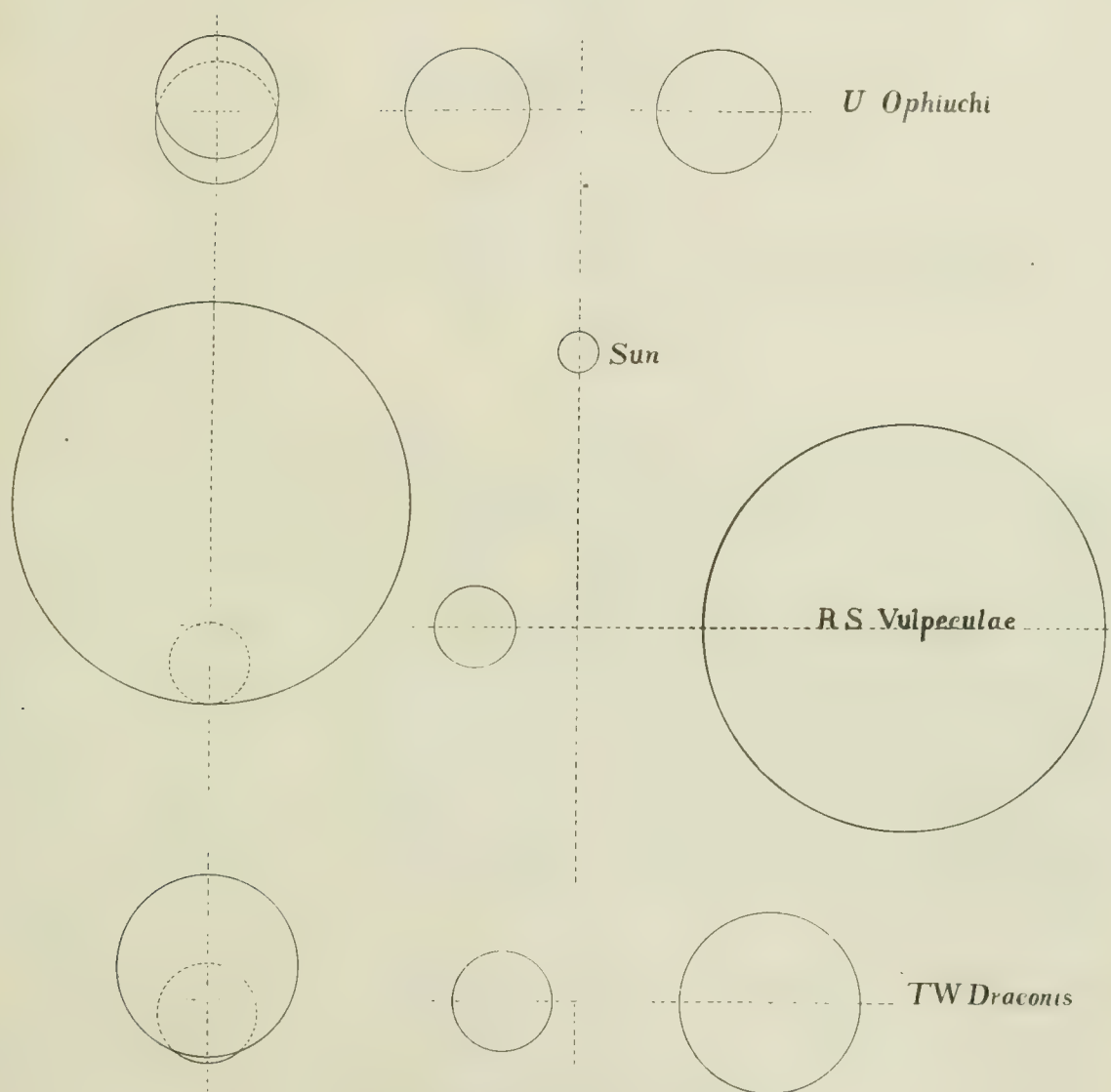
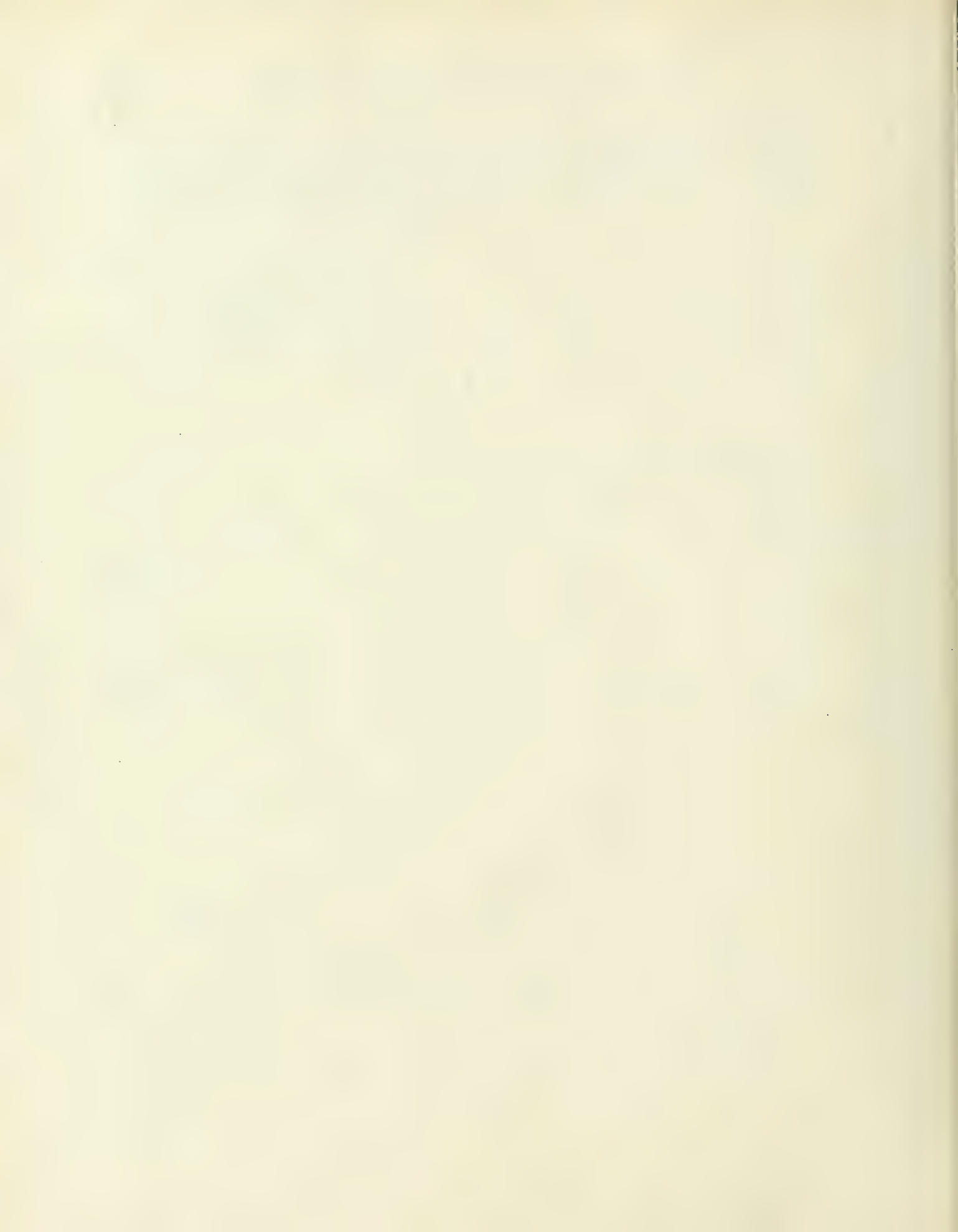
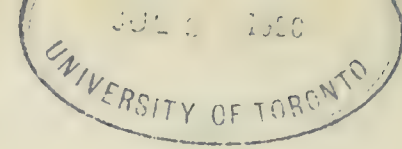


Fig. 4. Graphical Representation of Systems





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THE ORBIT OF THE SPECTROSCOPIC BINARY ι DELPHINI

BY W. E. HARPER.

This star ($1900\ \alpha = 20^h\ 33.0^m$, $\delta = +11^\circ\ 02'$, photographic magnitude 5.49, type A2) was announced as a spectroscopic binary by Adams in the *Astrophysical Journal*, Volume XXXV, page 178, from three plates made in 1911. The revised measures of these, kindly communicated by Professor Hale, are as given in the table of Observations. They have served in determining the period very closely as 262 revolutions have occurred between the first Mount Wilson plate and the last one made here. Apart from this they have not been used in the determination but they agree well with our curve, the residuals all being under 2 km. Six spectrograms were secured also by the writer while at the Dominion Observatory, Ottawa, and they have served to decide between two possible periods as adduced from connecting up the Mount Wilson observations with those made here at Victoria. The period finally accepted is 10.9960 days and the phases listed in the accompanying table are based on this value using the final value of periastron passage. All plates are given equal weight.

The spectrum is quite similar to that of Boss 4507 and Boss 4669, both recently investigated here, and has a multitude of metallic lines showing in addition to the intense and well-defined hydrogen lines and calcium K and the less strongly marked magnesium $\lambda 4481$. From 12 to 20 lines were measured on each plate and the error of a single plate should consequently be small, but for some reason or other it is considerably larger than might be expected. In the case of Boss 4669 the probable error of a plate was ± 1.0 km per sec.; in Boss 4507 the error was ± 1.2 km. per sec. while in this star it is nearly ± 1.9 km per sec. An examination of the plates reveals nothing in the nature of complexity of the lines though if two spectra were present the range is entirely too small for them to be resolved unless the masses were very disproportionate.

OBSERVATIONS OF α DEPHINI

Plate	Date	Julian Date G.M.T.	Phase	Velocity	Lines	Residuals O C
1911						
Mr. Wilson	Sept. 9	2,419,289.744	8.904	+19.6		+0.2
"	" 18	298.754	6.918	- 3.4		-1.0
"	Nov. 2	2,419,343.631	7.811	+ 9.3		+2.0
1919						
2027	May 20	2,422,099.953	4.137	-24.7	14	+0.0
2044	" 28	107.953	1.141	-20.5	11	-4.5
2054	" 30	109.941	3.129	-26.6	19	+2.0
2076	June 2	112.949	6.137	- 6.9	18	+2.8
2089	" 3	113.964	7.152	- 0.2	14	-0.2
2099	" 4	114.930	8.118	+12.1	15	+1.3
2114	" 6	116.955	10.143	+21.5	14	-2.0
2121	" 9	119.916	2.109	-27.2	12	+0.0
2130	" 11	121.933	4.126	-23.1	15	+1.6
2140	" 16	126.916	9.108	+18.8	14	-2.2
2150	" 17	127.941	10.133	+21.8	14	-1.8
2157	" 18	128.937	.133	+10.3	17	+2.3
2170	" 23	133.911	5.107	-15.9	16	+2.6
2189	" 26	136.937	8.133	+15.8	14	+4.9
2229	" 30	140.933	1.133	-12.9	18	+2.8
2477	July 21	161.883	.091	-12.2	13	+3.2
2568	" 28	168.961	7.169	+ 0.1	11	-0.2
2583	" 30	170.830	9.039	+21.0	16	+0.5
2601	Aug. 6	177.829	5.041	-24.1	13	+5.1
2618	" 7	2,422,178.895	6.107	-14.5	14	+4.4

NORMAL PLACES

	Mean Phase		Mean Velocity	Weight	Residuals O-C	
	Prel.	Final			Prel.	Final
1	7.929	8.126	+13.95	2	+2.37	+2.92
2	8.877	9.074	+19.90	2	- .27	- .92
3	9.941	10.138	+21.65	2	- .55	-2.12
4	10.912	.114	-11.25	2	+1.32	+3.14
5	.941	1.138	-16.70	2	-6.25	- .84
6	1.912	2.109	-27.2	1	-2.62	- .04
7	2.932	3.129	-26.6	1	+1.37	+2.02
8	3.934	4.131	-23.90	2	+ .89	+ .87
9	4.879	5.076	-20.00	2	-1.50	-1.43
10	5.926	6.123	-10.70	2	-1.46	- .90
11	6.965	7.162	- 0.05	2	-1.36	- .54

The observations were combined as in the preceding table and preliminary elements were obtained in the usual graphical way.

PRELIMINARY ELEMENTS

Period	$P = 10.9960$ days
Eccentricity	$e = .20$
Longitude of periastron	$\omega = 65^\circ$
Velocity of system	$\gamma = -4.65$ km
Semi-amplitude of range	$K = 25$ km
Periastron passage	$T = \text{J.D. } 2,422,096.013$

The period being so close to the even day there are practically only eleven points on the curve. Making the following transformations

$$\begin{aligned} x &= \delta\gamma \\ y &= \delta K \\ z &= K \cdot \delta e \\ u &= K \cdot \delta\omega \\ v &= \frac{K}{(1-e^2)^{3/2}} \cdot \mu \cdot \delta T = [1.19012] \delta T \end{aligned}$$

The observation equations are as given in the following table. Numbers 6 and 7 are given half weight.

OBSERVATION EQUATIONS FOR ϵ DELPHINI

1.....	1.000x	+ .637y	- .981z	+ .652u	- .669v	- 2.37 = 0
2.....	1.000	+ .974	- .526	+ .276	- .451	+ .27
3.....	1.000	+ 1.053	+ .847	- .429	+ .315	+ .55
4.....	1.000	+ .572	+ .568	- 1.054	+ 1.256	- 1.33
5.....	1.000	- .266	- 1.067	- 1.118	+ 1.217	+ 6.25
6.....	1.000	- .781	- .625	- .682	+ .518	+ 2.62
7.....	1.000	- .914	+ .505	- .145	- .038	- 1.37
8.....	1.000	- .790	+ .968	+ .304	- .341	- .89
9.....	1.000	- .543	+ .773	+ .597	- .506	+ 1.50
10.....	1.000	- .180	+ .108	+ .783	- .622	+ 1.46
11.....	1.000	+ .234	- .622	+ .807	- .687	+ 1.36

From these were obtained the normal equations

$$\begin{aligned} 20.000x + 1.687y + .016z + .809u - .496v + 14.870 &= 0 \\ 9.180 &- 1.946 &- .513 &+ .344 &- 7.076 \\ 11.347 &- .077 &+ .086 &- 12.649 \\ &10.004 &- 10.002 &- 10.461 \\ &10.348 &+ 11.982 \end{aligned}$$

resulting in the corrections as follows

$$\begin{aligned} \delta\gamma &= - .85 \text{ km} \\ \delta K &= + 1.22 \text{ km} \\ \delta e &= + .052 \\ \delta\omega &= - 4.19^\circ \\ \delta T &= - .197 \text{ days} \end{aligned}$$

The final values, then, with their probable errors are the following

FINAL ELEMENTS

$$P = 10.9960 \text{ days}$$

$$e = .252 \pm .025$$

$$\omega = 60.81 \pm 8.19$$

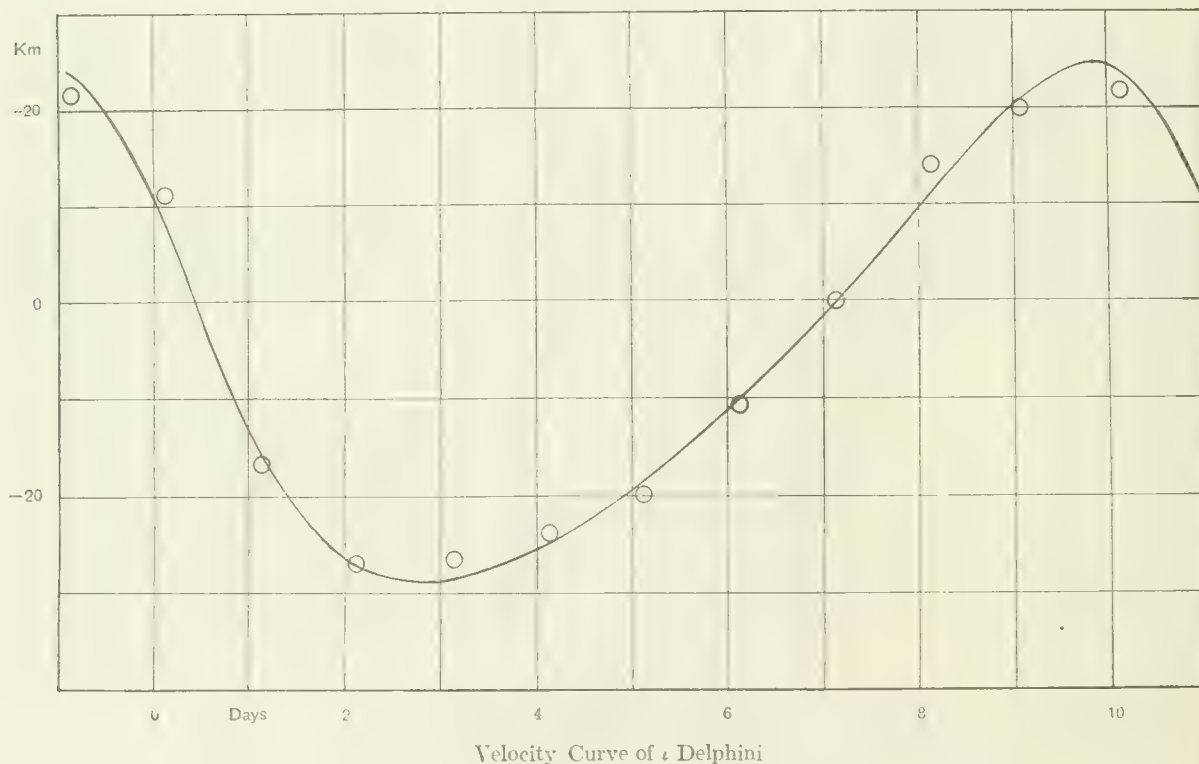
$$\gamma = -5.50 \text{ km} \pm .52 \text{ km}$$

$$K = 26.72 \text{ km} \pm .73 \text{ km}$$

$$T = \text{J.D. } 2,422,095.816 \pm .237 \text{ days}$$

$$a \sin i = 3,909,500 \text{ km}$$

$$\frac{m_1 \sin i}{(m + m_1)^2} = .020 \odot$$

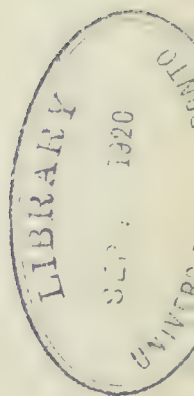


The solution improved the agreement considerably, though, as stated previously, the probable error of ± 1.9 for a plate is much larger than was hoped for from the character of the spectral lines. The graph represents the final elements, the grouped velocities being plotted.

Dominion Astrophysical Observatory,
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THE ORBITS OF THE SPECTROSCOPIC COMPONENTS
OF BOSS 5026

BY W. E. HARPER

This star (1900 $\alpha = 19^h 36.4^m$, $\delta = +54^\circ 44'$, photographic magnitude 6.3, type F5) was found to be a binary from the double lines shown on the first plate made. Twenty-nine plates were secured during the summer, all but four of which have been used in the present solution. These four, taken before the approximate period was known, fall at a phase in the orbit where the spectra are partially superposed and hence are unmeasurable. Of the remaining twenty-five all but four have both components measurable, so that the determination of the orbit rests on the equivalent of forty-six plates. All were made on Seed 30 emulsion with the single prism spectrograph, which has a dispersion at the central ray $\lambda 4200$ of 25.7 angstroms per millimetre.

The spectra of the two components are quite similar, the difference in intensities being barely sufficient to enable one to tell from inspection to which component each set of lines belongs. The lines of both components are fuzzy in nature, but as about a dozen on the average were measured in each case, a fairly reliable result was obtained, the probable error of a plate for component 1 (the one with the more intense lines) being ± 2.1 , and for the other ± 2.5 km. per sec. The masses, as may be expected, are very nearly equal, component 2 having a mass 0.986 times that of component 1.

In the table of observations following the phases are reckoned from the final value of periastron passage using the corrected period 7.6383 days.

OBSERVATIONS OF BOSS 5026

Plate Number	Date	Julian Date	Phase	Component 1			Component 2		
				Vel.	Lines	O-C	Vel.	Lines	O-C
	1919								
2472	July 21.....	2,422,161.798	6.230	+ 25.7	4	-6.2	- 75.1	4	-11.3
2489	" 22.....	162.797	7.229	+106.0	10	+2.9	-125.1	5	+10.9
2528	" 26.....	166.781	3.575	- 49.2	3	+0.3	+ 25.6	3	+ 6.9
2545	" 27.....	167.800	4.594	- 20.5	15				
2554	" 28.....	168.750	5.544	- 14.6	16				
2683	Aug. 14.....	185.782	7.299	+110.6	11	+4.7	-137.7	9	+ 1.1
2716	" 15.....	186.819	0.698	- 55.7	5	-6.5	+ 16.5	5	- 1.9
2730	" 18.....	189.687	3.566	- 50.3	3	-0.8	+ 23.2	3	+ 4.5
2750	" 19.....	190.730	4.609	- 18.7	21				
2786	" 21.....	192.724	6.603	+ 54.8	16	-0.5	- 87.2	14	+ 0.4
2801	" 22.....	193.704	7.583	+ 87.5	10	-0.8	-117.4	10	+ 3.6
2815	" 24.....	195.747	1.987	- 66.8	10	+4.5	+ 44.3	8	+ 3.5
2873	Sept. 1.....	203.731	2.332	- 66.8	7	+0.5	+ 39.0	7	+ 3.3
2881	" 6.....	208.735	7.337	+110.1	20	+3.4	-137.7	13	+ 1.9
2888	" 7.....	209.694	0.658	- 47.8	3	-2.1	+ 12.1	3	- 2.7
2908	" 9.....	211.668	2.632	- 61.3	10	+5.0	+ 39.6	8	+ 3.9
2924	" 12.....	214.664	5.628	- 16.5	19				
2943	" 14.....	216.695	7.659	+ 72.8	11	-1.1	-107.7	9	- 1.4
2980	" 16.....	218.660	1.986	- 70.8	13	+0.5	+ 40.1	9	- 0.7
3013	" 20.....	222.750	6.076	+ 25.6	6	+1.8	- 57.5	5	- 1.9
3037	" 21.....	223.666	6.992	+ 86.4	14	-0.8	-116.7	11	+ 3.6
3038	" 21.....	223.689	7.015	+ 82.8	15	-4.4	-126.7	13	- 6.4
3065	" 23.....	225.673	1.360	- 72.5	14	-0.5	+ 42.5	13	+ 1.0
3142	Oct. 6.....	238.609	6.658	+ 55.3	16	-3.8	- 95.2	14	- 3.8
3177	" 14.....	2,422,246.595	7.005	+ 88.3	12	+1.1	-120.3	12	+ 0.1

The period was obtained early in the observations, thus avoiding to a large extent useless plates at phases where the lines would be hopelessly mixed. In addition, this knowledge of the general form of the curve made possible the securing of separated spectra close to the crossing points by narrowing the collimator slit from its usual width of 0.051 mm. Nicely resolved lines were secured where the difference in velocity was of the order of 70 km. per sec., and in one case a difference of 60 km. gave lines clearly double in the violet region.

From the preliminary elements given later observation equations were built up according to the notation of Lehmann-Filhés, modified to suit cases of double spectra*, and a least-squares solution effected. As no early observations existed whereby the preliminary value of the period might be corrected, this term was also included in the solution. This practically necessitated treating all the observations separately, and only where they were taken on one night or where they fell on a smooth part of the curve was this principle departed from. In this connection the four plates showing single lines

* Dominion Observatory Publications, Vol. I, page 327.

and which group themselves symmetrically about one of the crossing points were formed into one normal place. By making the following transformations a set of 35 observation equations involving the 7 unknowns γ , K_1 , K_2 , e , ω , P and T were built up. The weights of each are as given in the last column.

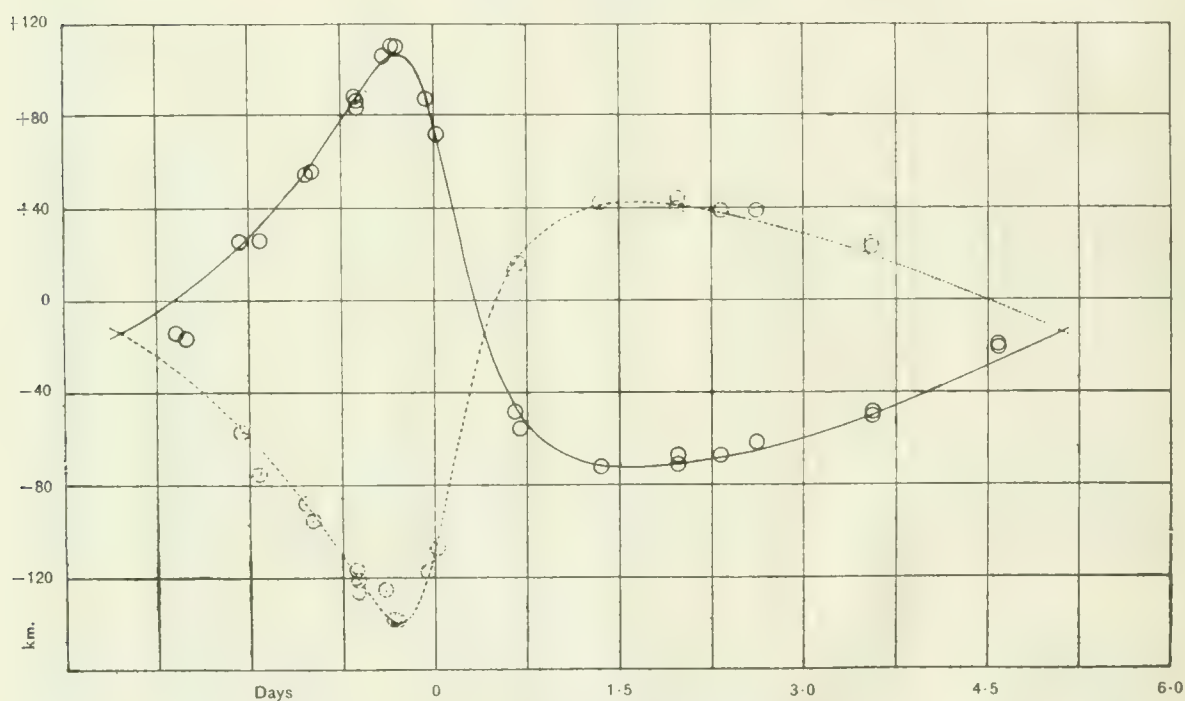
$$\begin{aligned}x &= \delta\gamma \\y &= \delta K_1 \\z &= \delta K_2 \\u &= 92 \cdot \delta e \\v &= 92 \cdot \delta \omega \\w &= [3 \cdot 23104] \delta P \\l &= [2 \cdot 11385] \delta T\end{aligned}$$

OBSERVATION EQUATIONS FOR BOSS 5026

1	1.000x	+ .431y	.000z	- .982u	+ .589v	- .064w	- .377l	-2.200=0	0.6
2	1.000	+ .502	.000	-1.114	+ .582	+ .173	- .412	+4.200	0.4
3	1.000	+ .760	.000	-1.447	+ .511	+ .060	- .544	-1.100	1.6
4	1.000	+ .819	.000	-1.480	+ .484	- .200	- .572	+3.800	1.6
5	1.000	+1.122	.000	-1.224	+ .248	- .134	- .668	+2.400	2.5
6	1.000	+1.134	.000	-1.191	+ .234	- .287	- .668	- .200	1.2
7	1.000	+1.297	.000	- .420	- .039	+ .215	- .523	-2.900	1.0
8	1.000	+1.347	.000	+ .092	- .205	+ .060	- .333	-2.900	1.1
9	1.000	+1.364	.000	+ .417	- .315	- .008	- .166	-0.900	2.0
10	1.000	+1.184	.000	+1.131	- .987	- .136	+1.363	+5.200	1.0
11	1.000	+ .986	.000	+ .479	-1.195	+ .245	+1.883	+1.700	1.1
12	1.000	- .384	.000	-1.213	-1.068	+ .039	+ .650	-3.800	0.3
13	1.000	- .412	.000	-1.093	-1.034	- .100	+ .587	+1.500	0.5
14	1.000	- .630	.000	+ .538	- .479	+ .007	+ .031	-1.700	1.4
15	1.000	- .603	.000	+ .966	- .171	- .003	- .071	-2.900	2.0
16	1.000	- .541	.000	+1.024	+ .007	- .004	- .102	-2.000	1.5
17	1.000	- .356	.000	+ .779	+ .281	+ .037	- .141	+ .800	0.6
18	1.000	+ .023	.000	- .076	+ .529	+ .041	- .225	+3.500	2.5
19	1.000	.000	- .431	+ .982	- .589	+ .064	+ .377	+1.600	0.5
20	1.000	.000	- .502	+1.114	- .582	- .173	+ .412	+12.700	0.4
21	1.000	.000	- .760	+1.447	- .511	- .060	+ .544	+1.000	1.4
22	1.000	.000	- .819	+1.480	- .484	+ .200	+ .572	+3.600	1.4
23	1.000	.000	-1.122	+1.224	- .248	+ .134	+ .668	+2.200	2.0
24	1.000	.000	-1.134	+1.191	- .234	+ .287	+ .668	- .300	1.2
25	1.000	.000	-1.297	+ .420	+ .039	- .215	+ .523	-10.500	0.5
26	1.000	.000	-1.347	- .092	+ .205	- .060	+ .333	-2.500	0.9
27	1.000	.000	-1.364	- .417	+ .315	+ .008	+ .166	-4.000	1.3
28	1.000	.000	-1.184	-1.131	+ .987	+ .136	-1.363	-7.800	1.0
29	1.000	.000	- .986	- .479	+1.195	- .245	-1.883	+ .700	0.9
30	1.000	.000	+ .384	+1.213	+1.068	- .039	- .650	+7.000	0.3
31	1.000	.000	+ .412	+1.093	+1.034	+ .100	- .587	+5.200	0.5
32	1.000	.000	+ .630	- .538	+ .479	- .067	- .031	- .800	1.3
33	1.000	.000	+ .603	- .966	+ .171	+ .003	+ .071	-3.000	1.5
34	1.000	.000	+ .541	-1.024	- .007	+ .004	+1.024	-5.800	1.8
35	1.000	.000	+ .356	- .779	- .281	- .037	+ .141	-7.900	0.5

NORMAL EQUATIONS

$$\begin{array}{rcccccccc}
 39.800x & +11.541y & -9.015z & -0.470u & +1.083v & +0.089w & -0.092l & -8.560=0 \\
 & 18.686 & +0.000 & -8.922 & -0.221 & -0.474 & -2.376 & +14.672 \\
 & & 14.806 & -7.509 & -0.015 & -0.619 & -0.972 & +5.959 \\
 & & & 38.665 & -10.589 & +2.028 & +13.284 & +33.860 \\
 & & & & 11.027 & -0.717 & -11.447 & -7.071 \\
 & & & & & 0.691 & +1.366 & -1.518 \\
 & & & & & & 18.914 & +7.589
 \end{array}$$



Radial Velocity Curves of Boss 5026 showing Individual Observations.

The solution of these equations gave small corrections to the preliminary elements, as may be noted in the table following. One solution was seen to be sufficient, as judged by the agreement of the ephemeris residuals and those contained by substituting directly in the observation equations. The sum of the squares of the residuals for the normal places was reduced from 527 to 386, about 27 per cent.

TABLE OF ELEMENTS

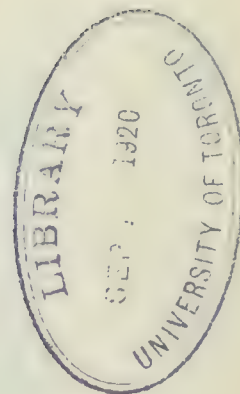
Element	Preliminary	Final
Period.....P	7.635 days	7.6383 days \pm .0019 days
Eccentricity.....e	.55	.527 \pm .006
Longitude of apse..... ω_1	48°	46°.74 \pm 0°.81
Longitude of apse..... ω_2	228°	226°.74 \pm 0°.81
Velocity of system..... γ	-16.26 km.	-15.59 km. \pm 0.36 km.
Semi-amplitude primary.....K ₁	92 km.	89.81 km. \pm 0.69 km.
Semi-amplitude secondary.....K ₂	92 km.	91.12 km. \pm 0.71 km.
Periastron passage.....T	J.D. 2,422,201.405	J.D. 2,422,201.398 \pm 0.007
Semi major axis.....a ₁ sin i	.....	8,017,000 km.
“ “.....a ₂ sin i	.....	8,134,000 km.
Mass primary.....m ₁ sin i	.....	1.854 \odot
Mass secondary.....m ₂ sin i	.....	1.827 \odot

The graph shown represents the final elements, the continuous curve being that of the so-called component 1, the dotted curve that of the other. Individual observations are plotted.

Dominion Astrophysical Observatory,
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ONE HUNDRED SPECTROSCOPIC BINARIES.

BY J. S. PLASKETT, W. E. HARPER, R. K. YOUNG AND H. H. PLASKETT.

The following list of spectroscopic binaries contains the first 100 binaries discovered at this observatory. Four preliminary announcements of 75 binaries have been made in the Journal of the Royal Astronomical Society, XII p. 460, XIII pp. 59, 191, 372, and the issue of this number was delayed until 100 had been obtained.

These binaries have been discovered in the course of the regular radial velocity work of this observatory. The programme of stars at present under observation consists of 772 stars selected from the Preliminary General Catalogue of Boss. This selection was made in co-operation with the Mt. Wilson Observatory, also engaged in observing Boss stars, the plan being to so divide the unobserved stars in Boss that the radial velocities of all within reach at the two observatories would be completed about the same minimum time. All the stars on this list are north of the equator and range in brightness between about the 5th and 10th magnitudes, about 40 being fainter than the 8th magnitude.

The telescope and spectrograph with which these observations are being made has been fully described in Vol. 1, No. 1 of these publications and only a short summary of the optical constants need be repeated here. The telescope has an effective aperture of 72 inches (182.9 cm) the focal length of the principal mirror being 361.3 inches (903.3 cm). The spectrograph is used with the Cassegrain combination, whose equivalent focal length is 108 feet (32.92 metres). A hole in the centre of the main mirror enables the spectrograph to be attached at the bottom of the telescope tube along the optical axis of the telescope, a very convenient position. The spectrograph which is arranged for either one, two or three prisms has been used with one prism only. Owing to war conditions, material for the three prisms ordered from the Brashear Co. could not be obtained and from May 7, 1918 to August 12, 1919, a 60° Hilger prism of flint glass 0.118, kindly loaned by Prof. Chant of the University of Toronto, was used. This was then replaced by the one now in use, a 62° prism of slightly denser glass also made by the Hilger Co., and of exquisite defining power. The collimator is of 2½ inches (63 mm) aperture and 45 inches (1,143 mm) focal length. Three cameras are provided of 3 inches (76 mm) aperture and of 16.5 inches (419 mm), 28 inches (711 mm), and 38 inches (965 mm) focal length respectively. With the first prism only the medium focus, 28 inch camera, giving a linear

dispersion at $H\gamma$ of nearly 35 Å per millimetre was used. With the new prism the three cameras will give linear dispersions of 49, 29, and 22 Å per millimetre respectively. The medium focus camera is used for the major part of the stars, and only for those around the 8th magnitude or fainter will the short focus camera be required. As previously stated the instrument gives beautiful definition and the measures show very satisfactory accuracy.

Stars of the "early" types B and A are measured on micrometer microscopes, a Toepfer and Gaertner being available. All stars of type between F0 and M are measured on the Hartmann Spectro-Comparator, unless, as occurs in a few cases, the lines are broad and diffuse when more reliable values can be obtained on the micrometer microscope. The probable error of a single plate measured on the spectro-comparator is frequently below one kilometre per second, while on the micrometer microscope it depends altogether upon the number and sharpness of the lines with a minimum value of one kilometre per second increasing to as much as five or six when the lines are few in number and very broad and difficult to set on.

As in all lists of spectroscopic binaries, a number of these have such a small range as to render the chances of obtaining a satisfactory orbit very small. However, there can be no doubt of the reality of the variation in all the stars published. Several more not included in the list show a greater range than can be readily explained by errors of observation and measurement and yet not sufficient to justify announcement. The best that can be done with such stars as well as with those of small range in the list is to obtain a sufficient number of well distributed spectra of each, say not less than twelve, to enable the velocity of the system to be determined with satisfactory accuracy. For the binaries of larger range in which a fairly good orbit is possible it is believed that sufficient plates should be secured to enable the elements to be determined.

To the end that the data given here may be sufficient to enable an intelligent selection of those suitable for investigation to be made by anyone, full information is given in the list of the date, measured velocity and quality of the plates. To this list is appended full notes giving the character of the spectrum and the suitability for measurement of each star.

It is to be noted that in the lists previously published a serial number was given to each star. This was done for convenience of reference in the notes and is continued in the present list. But owing to the rearrangement of the 100 binaries in order of right ascension rather than in order of discovery, the numbers in the two lists are not the same. However, as they are only used for referring to the notes, no confusion need thereby be caused as the binary will always be referred to by its Boss or Harvard number and by its right ascension and declination.

In the table the first column gives the number for reference in the notes, the second the Boss and Harvard numbers, the third the right ascension and declination for 1900. The fourth column gives the spectral type and visual magnitude and the fifth and sixth the date and Julian date of the observation. The seventh column gives the radial velocity, the eighth the quality of the individual plates as regards suitability of exposure and development, while the last column gives the initial of the discoverer, P standing for J. S. Plaskett, H for W. E. Harper, Y for R. K. Young and P' for H. H. Plaskett.

To explain the wide differences in the numbers discovered by the various observers, 44, 42, 11 and 3 binaries respectively, it should be stated that J. S. Plaskett and R. K. Young have been observing since the beginning, May 7, 1918, W. E. Harper since April 15, 1919 and H. H. Plaskett since October 4, 1919.

These 100 binaries have been discovered in the measurement of two or more spectra of 574 stars. In many of these stars all the spectra measured have been obtained in one season and it is probable when additional plates in the following season have been obtained that some now considered single, especially in types G to M, may prove to be double. In any case the proportion of spectroscopic binaries among stars observed will be about one to five or six, practically the same ratio as found at Lick and elsewhere. A preponderating proportion of these binaries, 98, are of types B, A and F and only 2 of types G to M. Out of 65 stars of B type observed 21 are binary, of 220 A type stars 57 are binary and of 116 F type stars 20 are binary. Of the 45 G type stars measured only 1 binary, and of 112 K type stars also only 1 binary has so far been obtained, while of the 16 M type stars measured none are binary. Of the 306 spectroscopic binaries in Campbell's second catalogue there are 37 of G type, 37 of K type and 2 of M type, an entirely different proportion to that obtained here. The difference may be decreased, more G and K type binaries discovered, when the observations have been carried over a longer period. Also it is probable that binaries with a small range, 5 km or less, whose binary character can be certainly established with three prism dispersion such as used at the Lick Observatory where most of these late type binaries were discovered, could not definitely be placed in the binary class with a dispersion only one-third as great. Nevertheless, the discrepancy appears greater than can be ascribed to these two considerations and an explanation must await further data.

No.	Star	R.A. 1900 Dec. 1900	Type Vis. Mag.	Date	Julian Day G.M.T.	Radial Velocity	Quality	Dis- coverer
1	Boss 108 H.R. 137	00 ^h 28.6 ^m +66° 12'	B9 6.42	1918 Oct. 6	2,421,873.843	-21.4	Fair	P
				" 8	1,875.794	-10.8	"	
				" 19	1,886.836	-8.5	Good	
				Nov. 26	1,924.691	-35.1	"	
				" 26	1,924.707	-36.6	"	
2	Boss 282 H.R. 361	01 ^h 08.5 ^m +07° 03'	A5 5.6	1918 Oct. 8	2,421,875.882	-1.2	Good	P
				" 27	1,894.826	+22.9	"	
				Nov. 24	1,922.762	+20.3	"	
				Dec. 29	1,957.660	-2.7	Weak	
				" 29	1,957.674	-17.7	Fair	
3	Boss 283 H.R. 362	01 ^h 08.5 ^m +07° 03'	F8 6.5	1919 Jan. 7	1,966.697	+28.5	Good	P
				1918 Oct. 8	2,421,875.866	+44.9	Good	
				" 27	1,894.842	+13.6	Weak	
				Nov. 24	1,922.776	-8.7	Good	
				1919 Jan. 7	1,966.682	+41.9	"	
4	Boss 307 H.R. 395	01 ^h 17.9 ^m +37° 12'	A 5.5	1918 Sept. 11	2,421,848.907	+11.6	Good	Y
				Oct. 28	1,895.762	{ -44.4 +66.8 }	"	
				Nov. 20	1,918.750	+14.1	"	
				" 20	1,918.765	+17.0	"	
				Dec. 20	1,948.687	+15.5	"	
5 H.R. 407	01 ^h 20.1 ^m +23° 00'	F5 6.1	" 20	1,948.697	+16.6	"	P
				1918 Aug. 22	2,421,828.985	-23.4	Good	
				Oct. 8	1,875.911	-3.2	"	
				" 20	1,887.806	-17.0	"	
				Nov. 24	1,922.794	-20.2	"	
6	Boss 443	01 ^h 52.9 ^m +75° 01'	A ₀ 7.0	1919 Sept. 9	2,422,211.973	-5.0	Weak	H
				Oct. 6	2,238.897	-88.5	Fair	
				" 18	2,250.843	-39.1	"	
7	Boss 480 H.R. 620	02 ^h 02.5 ^m +37° 23'	A2 4.8	1918 Oct. 6	2,421,873.889	+13.8	Good	P
				" 20	1,887.822	+26.0	"	
				" 27	1,894.859	+36.4	"	
				Nov. 24	1,922.828	-22.8	"	
8	Boss 497 H.R. 642	02 ^h 06.6 ^m +29° 50'	G ₀ 5.2	1919 Oct. 3	2,422,235.906	{ -76.7 +37.0 }	Fair	H
				" 13	2,245.794	-9.7	"	
				" 18	2,250.803	{ -75.3 +26.9 }	"	
9	Boss 497	02 ^h 06.6 ^m +29° 50'	A5 6.4	1919 Oct. 13	2,422,245.817	-91.3	Good	H
				" 18	2,250.821	+34.7	Fair	
				" 24	2,256.852	-106.6	Weak	
10	Boss 606 H.R. 782	02 ^h 34.8 ^m +26° 38'	A2 5.4	1918 Oct. 6	2,241,873.906	+2.0	Good	P
				" 19	1,886.894	-10.6	"	
				" 27	1,894.869	+24.7	"	
				Nov. 24	1,922.837	+15.9	"	

No.	Star	R.A. 1900 Dec. 1900	Type Vis. Mag.	Date	Julian Day G.M.T.	Radial Velocity	Quality	Dis- coverer
11	H.R. 894	02 ^h 53.8 ^m +37° 45'	B9 5.9	1918 Sept. 11	2,421,848.958	-33.1	Good	Y
				Nov. 22	1,920.815	-22.5	"	
				" 22	1,920.830	-11.4	Weak	
				Dec. 20	1,948.723	-8.1	Good	
				" 20	1,948.739	-4.8	"	
12	Boss 787 H.R. 1041	03 ^h 22.0 ^m +33° 28'	Ao 5.6	1918 Nov. 20	2,421,918.866	-9.7	Fine	Y
				Dec. 16	1,944.769	+19.8	"	
				1919 Jan. 10	1,969.701	+6.4	"	
13	Boss 809 H.R. 1078	03 ^h 26.9 ^m +39° 34'	Ao 5.8	1918 Nov. 22	2,421,920.870	-20.0	Good	Y
				Dec. 16	1,944.782	+20.5	"	
				1919 Jan. 10	1,969.715	+103.9	"	
				" 29	1,988.647	-79.1	"	
14	Boss 836 H.R. 1118	03 ^h 34.8 ^m +25° 00'	Ao 6.2	1918 Oct. 8	2,421,875.926	+42.1	Good	P
				" 27	1,894.901	-14.7	Fair	
				Nov. 26	1,924.856	-19.6	Good	
				Dec. 10	1,938.801	+43.1	"	
15	Boss 866 H.R. 1158	03 ^h 40.8 ^m +63° 00'	A3 5.96	1918 Oct. 29	2,421,896.906	-23.6	Good	P
				Dec. 22	1,950.769	-34.1	Fair	
				1919 Jan. 19	1,978.696	-4.5	Good	
				" 19	1,978.707	+4.0	"	
16	Boss 943 H.R. 1268	04 ^h 00.5 ^m +27° 21'	Aop 5.3	1918 Dec. 20	2,421,948.812	+12.8	Good	Y
				" 30	1,958.731	+1.4	"	
				1919 Jan. 29	1,988.665	-17.0	"	
				Feb. 14	2,004.664	-7.9	Fair	
17	Boss 1004 H.R. 1351	04 ^h 14.3 ^m +13° 48'	Fo 5.6	1918 Oct. 20	2,421,887.885	+67.4	Fair	P
				Nov. 26	1,924.881	+59.8	Good	
				Dec. 10	1,938.806	+12.5	"	
				1919 Jan. 19	1,978.749	+12.5	"	
				Feb. 2	1,992.597	+52.4	"	
18	Boss 1013 H.R. 1368	04 ^h 16.4 ^m +13° 50'	A3 5.8	1918 Dec. 20	2,421,948.799	+12.8	Good	Y
				" 30	1,958.744	+47.4	"	
				1919 Jan. 31	1,990.657	+58.9	"	
19	Boss 1051 H.R. 1422	04 ^h 24.4 ^m +15° 25'	Fo 5.7	1918 Oct. 30	2,421,897.916	+48.8	Good	Y
				Dec. 16	1,944.808	+23.1	"	
				Jan. 31	1,990.689	+34.8	"	
20	Boss 1058 H.R. 1432	04 ^h 26.2 ^m +15° 38'	Fo 6.04	1919 Jan. 30	2,421,989.671	+53.2	Fair	P
				Feb. 2	1,992.622	+40.4	Good	
				" 11	2,001.678	+42.5	"	
				1919 Feb. 23	2,422,013.610	+39.0	Good	
				Mar. 20	2,038.640	+27.6	"	
21	Boss 1068 H.R. 1445	04 ^h 28.4 ^m +28° 46'	B9 5.7	1918 Nov. 26	2,421,924.891	+14.3	Fair	P
				Dec. 10	1,938.828	+6.4	Good	
				" 21	1,949.840	+3.4	"	
				1919 Jan. 19	1,978.771	+8.1	"	
				Mar. 8	2,026.636	+18.8	"	
				" 18	2,036.649	+22.0	"	

No.	Star	R.A. 1900 Dec. 1900	Type Vis. Mag.	Date	Julian Day G.M.T.	Radial Velocity	Quality	Dis- coverer
22	Boss 1085 H.R. 1471	04 ^h 32.4 ^m +20° 30'	B9 5.73	1918 Oct. 30	2,421,897.889	+ 1.8	Good	Y
				Nov. 1	1,899.863	-16.2	"	
				Dec. 30	1,958.775	-53.2	"	
				1919 Jan. 6	1,965.765	+ 6.0	"	
23	Boss 1122 H.R. 1519	04 ^h 40.5 ^m +11° 31'	A0 5.43	1918 Dec. 10	2,421,938.852	+32.1	Good	P
				" 14	1,942.872	+28.8	"	
				" 29	1,957.824	+45.8	"	
				1919 Jan. 30	1,989.690	+46.2	"	
24	Boss 1244 H.R. 1706	05 ^h 08.8 ^m +32° 35'	A2 5.14	1918 Dec. 14	2,421,942.905	+16.9	Good	P
				" 29	1,957.856	+16.9	"	
				1919 Jan. 7	1,966.822	-15.7	"	
				" 30	1,989.698	-25.7	"	
25	Boss 1273 H.R. 1750	05 ^h 14.7 ^m +27° 51'	B9 6.3	1918 Nov. 4	2,421,902.921	- 1.3	Good	Y
				Dec. 20	1,948.876	+24.5	"	
				" 30	1,958.801	+36.6	"	
				1919 Jan. 6	1,965.782	-28.8	"	
26	Boss 1276 H.R. 1751	05 ^h 14.9 ^m +57° 27'	A0 5.25	1919 Feb. 4	2,421,994.682	- 0.2	Good	P
				" 23	2,013.665	+17.5	"	
				Mar. 2	2,020.625	- 0.3	"	
				" 20	2,038.696	+12.9	"	
27	Boss 1336 H.R. 1847	05 ^h 26.4 ^m +16° 59'	B9 5.5	1918 Oct. 8	2,421,875.973	+ 0.1	Good	P
				" 19	1,886.965	+ 7.0	"	
				Dec. 10	1,938.879	+ 7.6	"	
				1919 Jan. 7	1,966.860	+17.8	Weak	
				" 30	1,989.709	+26.0	Fair	
				Mar. 2	2,020.640	+18.0	Good	
28	Boss 1337	05 ^h 26.4 ^m +16° 59'	A 6.8	1918 Oct. 19	2,421,886.977	+ 6.9	Good	P
				Dec. 10	1,938.896	+28.0	"	
				1919 Jan. 30	1,989.724	+23.2	Poor	
				Mar. 2	2,020.656	+21.3	Good	
29	Boss 1369 H.R. 1902	05 ^h 30.9 ^m +26° 52'	B8 5.7	1918 Nov. 4	2,421,902.958	+ 0.5	Good	Y
				1919 Jan. 10	1,969.728	+10.8	Fair	
				" 10	1,969.740	+14.7	Good	
				" 29	1,988.712	+ 8.8	Fair	
30	Boss 1410 H.R. 1969	05 ^h 38.1 ^m +56° 05'	A2 6.06	1919 Jan. 30	2,421,989.723	-15.9	Good	P
				Feb. 2	1,992.647	+14.5	"	
				" 2	1,992.656	+16.5	"	
				" 11	2,001.720	+55.4	"	
				" 23	2,013.694	+54.5	"	
				" 23	2,013.708	+28.1	"	
31	Boss 1452 H.R. 2027	05 ^h 46.0 ^m +59° 52'	A0 5.26	1918 Dec. 10	2,421,938.924	+21.0	Good	P
				" 21	1,949.892	+67.8	"	
				1919 Feb. 1	1,991.758	+ 6.2	"	
				" 2	1,992.683	-76.4	"	
				" 11	2,001.751	-60.1	"	
				" 11	2,001.759	-51.9	"	

No.	Star	R.A. 1900 Dec. 1900	Type Vis. Mag.	Date	Julian Day G.M.T.	Radial Velocity	Quality	Dis- coverer
32	Boss 1455 H.R. 2033	05 ^h 46.7 ^m +14° 09'	B9 5.57	1918 Dec. 30	2,421,958.827	+ 4.0	Good	Y
				1919 Jan. 6	1,965.810	- 6.1	"	
				" 10	1,969.831	- 9.1	"	
				Mar. 24	2,042.633	-12.9	"	
				Dec. 3	2,296.839	- 2.1	"	
33	Boss 1559 H.R. 2214	06 ^h 08.6 ^m +17° 57'	A5 5.74	1918 Nov. 4	2,421,902.966	+ 7.6	Good	Y
				Dec. 16	1,944.885	+38.4	"	
				1919 Jan. 29	1,988.746	+39.4	"	
34	Boss 1714 H.R. 2466	06 ^h 36.0 ^m +17° 45'	Ao 5.14	1919 Jan. 30	2,421,989.837	+25.9	Fair	P
				Feb. 4	1,994.708	+ 9.0	Good	
				" 16	2,006.819	+15.3	Fair	
				Mar. 20	2,038.709	+17.7	Good	
				Nov. 25	2,288.991	+41.7	Fair	
35	Boss 2013 H.R. 2950	07 ^h 34.8 ^m +05° 28'	Ao 5.8	1918 Dec. 20	2,421,948.919	+ 6.4	Fair	Y
				Jan. 6	1,965.892	+19.0	"	
				" 29	1,988.814	+26.3	Good	
				" 31	1,990.789	+33.4	"	
				Mar. 21	2,039.647	+ 6.9	"	
36	Boss 2022 H.R. 2969	07 ^h 36.5 ^m +50° 40'	Ao 5.28	1918 Dec. 29	2,421,957.954	-19.0	Good	P
				1919 Mar. 18	2,036.720	+25.6	"	
				" 18	2,036.732	+16.8	"	
				" 23	2,041.698	+17.2	"	
				" 23	2,041.709	+ 5.3	"	
37	Boss 2142 H.R. 3167	08 ^h 00.2 ^m +43° 34'	Ao 6.2	1919 Feb. 11	2,422,001.823	+23.0	Good	H
				" 23	2,013.774	+68.8 -60.7	"	
				Mar. 18	2,036.762	+10.7	Fine	
				April 6	2,055.653	+10.3	"	
				" 6	2,055.668	+14.6 -65.8 +86.1	"	
38	Boss 2173 H.R. 3215	08 ^h 06.9 ^m +29° 57'	Aop 5.6	1918 Dec. 16	2,421,944.962	+27.8	Good	Y
				" 16	1,944.978	+21.8	"	
				" 30	1,958.832	+16.7	"	
				1919 Mar. 21	2,039.693	+ 7.4	"	
39	Boss 2251 H.R. 3329	08 ^h 22.7 ^m +24° 28'	A5 6.1	1918 Dec. 20	2,421,948.941	+15.6	Fair	Y
				1919 Jan. 10	1,969.888	+ 6.7	Good	
				Feb. 17	2,007.819	+20.0	"	
				Mar. 24	2,042.696	+ 1.7	"	
40	Boss 2432 H.R. 3603	08 ^h 58.5 ^m +48° 55'	F5 5.59	1918 Dec. 29	2,421,956.995	-12.6	Good	P
				1919 Feb. 11	2,001.865	+ 7.2	"	
				" 23	2,013.843	+10.6	"	
				Mar. 18	2,036.795	+12.8	"	

No.	Star	R.A. 1900 Dec. 1900	Type Vis. Mag.	Date	Julian Day G.M.T.	Radial Velocity	Quality	Dis- coverer
41	Boss 2463 H.R. 3648	09 ^h 06.4 ^m +61° 50'	F8 5.23	1919 Feb. 5	2,421,995.859	-50.6	Fine	Y
				Mar. 19	2,037.700	+ 8.2	"	
				April 14	2,063.678	- 6.6	"	
				" 25	2,074.662	-48.3	"	
42	Boss 2634 H.R. 3889	09 ^h 44.2 ^m +21° 39'	F0 6.01	1919 Feb. 11	2,422,001.903	+30.2	Good	P
				" 23	2,013.850	+23.7	Fair	
				Mar. 20	2,038.808	+42.4	Good	
				April 1	2,050.776	+54.0	"	
43	Boss 2672 H.R. 3937	09 ^h 52.8 ^m +12° 55'	A0 5.18	1919 Feb. 23	2,422,013.896	+28.6	Good	P
				Mar. 8	2,026.838	+31.9	"	
				" 23	2,041.792	+35.6	"	
				April 13	2,062.726	+ 7.3	"	
				Nov. 26	2,289.061	+40.9	"	
44	Boss 2951 H.R. 4322	11 ^h 02.3 ^m +23° 52'	A2 6.39	1918 May 13	2,421,727.687	-17.1	Weak	Y
				Dec. 31	1,959.002	- 7.8	Good	
				1919 Jan. 6	1,965.962	-15.0	"	
				Mar. 21	2,039.817	-12.6	"	
				April 23	2,072.703	+ 7.5	"	
45	Boss 3102 H.R. 4536	11 ^h 44.5 ^m +35° 29'	F5 5.76	1919 Mar. 20	2,422,038.826	+31.5	Good	P
				April 13	2,062.752	-10.8	"	
				" 26	2,075.764	+16.9	"	
46	Boss 3354 H.R. 4892	12 ^h 48.3 ^m +83° 58'	A0 5.81	1919 Mar. 8	2,422,026.907	+ 0.1	Good	P
				" 25	2,043.813	-88.8	"	
				April 1	2,050.812	+106.2	"	
						-98.8	"	
						+110.2	"	
47	Boss 3555 H.R. 5182	13 ^h 42.1 ^m +26° 12'	F5 5.91	1919 Mar. 19	2,422,037.946	+ 7.2	Good	Y
				April 11	2,060.836	-34.8	"	
				" 14	2,063.817	+38.8	"	
				" 23	2,072.802	+24.0	"	
						+10.4	"	
48	Boss 3652 H.R. 5328	14 ^h 09.9 ^m +52° 16'	A5 6.75	1918 May 20	2,421,734.799	-28.6	Good	Y
						-29.7	"	
				June 17	1,762.755	-27.7	"	
				July 12	1,787.711	-19.4	"	
				1919 Mar. 24	2,042.907	-27.1	"	
				April 7	2,056.903	-22.3	"	
				May 19	2,098.732	-19.7	"	
49	Boss 3674 H.R. 5360	14 ^h 13.8 ^m +51° 46'	A 6.09	1918 May 22	2,421,736.718	-32.3	Good	Y
						-29.4	"	
				June 17	1,762.731	-10.0	"	
				July 11	1,786.689	-16.2	Poor	
				" 12	1,787.694	-11.2	Fair	
				Mar. 21	2,039.986	- 5.6	Good	
				April 7	2,056.762	- 7.5	"	
				June 6	2,116.729	- 4.8	"	

No.	Star	R.A. 1900 Dec. 1900	Type Vis. Mag.	Date	Julian Day G.M.T.	Radial Velocity	Quality	Dis- coverer
50	Boss 3909	15 ^h 16.3 ^m +50° 35'	Ao 7.8	1919 April 28	2,422,077.823	-26.0	Weak	H
				May 5	2,084.825	-3.0	Good	
				" 20	2,099.799	-28.0	Fair	
				" 28	2,107.777	-5.0	Poor	
				" 30	2,109.725	+14.0	Fair	
				June 9	2,119.748	-22.0	"	
				July 7	2,147.748	-4.0	Good	
51	Boss 4098 H.R. 6004	16 ^h 02.9 ^m +10° 10'	A 5.63	1918 May 21	2,421,735.848	-29.1	Good	Y
				" 24	1,738.808	-22.6	"	
				June 14	1,759.774	-37.9	"	
				July 16	1,791.731	-36.0	Fair	
				1919 May 4	2,083.881	-20.3	Good	
				June 2	2,112.783	-27.7	"	
52	Boss 4121 H.R. 6034	16 ^h 06.9 ^m +77° 04'	Ao 5.6	1918 May 20	2,421,734.841	-44.7	Good	Y
				June 20	1,765.789	-23.5	"	
				July 23	1,798.703	-41.0	Fair	
				1919 June 4	2,114.827	-29.0	Good	
				July 20	2,160.698	-16.1	"	
53	Boss 4123 H.R. 6036	16 ^h 07.1 ^m +58° 12'	Ao 6.31	1918 May 22	2,421,736.823	+11.5	Fair	P
				June 19	1,764.756	-1.6	Good	
				" 26	1,771.731	-26.9	"	
				July 24	1,799.692	-8.0	"	
54 H.R. 6169	16 ^h 30.9 ^m +17° 15'	Ao 6.27	1918 July 1	2,421,776.753	+2.1	Good	Y
				1919 April 21	2,070.936	-31.2	"	
				June 1	2,111.836	-56.6	"	
				July 13	2,153.732	-28.8	Fair	
55 H.R. 6385	17 ^h 06.1 ^m +12° 35'	Ao 6.46	1918 June 28	2,421,773.821	+28.3	Good	Y
				1919 May 4	2,083.922	-32.0	"	
				July 6	2,146.765	+20.5	"	
				Aug. 29	2,200.661	-28.5	"	
56	Boss 4411 H.R. 6469	17 ^h 18.4 ^m +40° 05'	F8 5.72	1918 May 26	2,421,740.931	+1.4	Good	P
				June 19	1,764.815	-1.9	"	
				1919 July 1	2,141.828	-22.7	"	
				" 17	2,157.817	-5.4	Fair	
				" 26	2,166.747	-9.3	Good	
				Aug. 28	2,199.655	-20.2	"	
57	Boss 4499 H.R. 6627	17 ^h 42.7 ^m +17° 46'	Ao 5.58	1919 May 5	2,422,084.965	+2.2	Good	H
				" 20	2,099.964	+13.5	"	
				June 16	2,126.853	-14.5	Fair	
				July 7	2,147.783	+1.2	Good	
58	Boss 4507 H.R. 6641	17 ^h 44.4 ^m +47° 39'	Ao 6.34	1919 May 28	2,422,107.927	-85.6	Weak	H
				" 31	2,110.808	-86.4	Fine	
				June 9	2,119.891	-28.3	Fair	
59 H.R. 6767	18 ^h 01.9 +41° 56'	Fo 6.42	1918 June 28	2,421,773.867	-19.1	Good	Y
				Sept. 16	1,853.609	-44.4	Fair	
				1919 July 2	2,142.816	-5.9	Good	
				" 23	2,163.793	-13.9	"	

No.	Star	R.A. 1900 Dec. 1900	Type Vis. Mag.	Date	Julian Day G.M.T.	Radial Velocity	Quality	Dis- coverer
60	Boss 4602 H.R. 6809	18 ^h 07.5 ^m +79° 59'	F5 6.18	1918 June 19	2,421,764.847	+10.5	Good	P
				" 28	1,767.804	+17.1	"	
				" 26	1,771.770	- 2.7	"	
				July 21	1,796.719	+21.8	"	
61 H.R. 6814	18 ^h 08.1 ^m +33° 26'	A2 5.85	1918 Aug. 22	2,421,828.710	- 7.1	Fair	P
				" 25	1,831.723	-38.6	Good	
				Sept. 22	1,859.669	-60.7	Poor	
				Nov. 5	1,903.564	-22.9	Good	
62	Boss 4614 H.R. 6826	18 ^h 09.8 ^m +38° 45'	A 5.88	1918 May 21	2,421,735.942	+23.1	Good	Y
				" 26	1,740.914	-17.1	"	
				June 19	1,764.828	- 8.9	"	
				1919 May 19	2,098.954	-29.6	"	
				July 6	2,146.823	-18.2	"	
63	Boss 4622 H.R. 6849	18 ^h 13.0 ^m +56° 34'	F0 6.41	1919 July 7	2,422,147.816	{ -83.0 +66.0	Good	H
				" 14	2,154.814	-122.0 + 73.0	Fair	
				" 15	2,155.832	-110.0 +108.0	"	
				" 18	2,158.788	+ 96.0 -116.0	Good	
				" 21	2,161.716	-102.0 + 95.0	Fair	
				" 22	2,162.745	-107.0 + 84.0	Good	
64	Boss 4644 H.R. 6877	18 ^h 17.1 ^m +28° 49'	A5 5.05	1918 June 26	2,421,771.824	-39.8	Good	P
				July 24	1,799.734	-28.9	"	
				Aug. 22	1,828.677	-21.6	"	
				" 25	1,831.739	-42.7	"	
				Oct. 13	1,880.591	-38.5	"	
				" 15	1,882.608	-30.8	"	
				" 24	1,891.604	-31.7	"	
65	Boss 4661 H.R. 6903	18 ^h 20.9 ^m +39° 27'	A2 5.04	1918 May 27	2,421,741.944	-41.1	Good	Y
				June 14	1,759.884	-23.3	"	
				July 5	1,780.794	-45.1	"	
				" 11	1,786.839	-22.6	"	
				Aug. 27	1,833.665	-19.7	"	
				Sept. 20	1,857.650	-43.4	Fair	
				1919 July 23	2,163.781	-26.4	Good	
66	Boss 4669 H.R. 6917	18 ^h 22.1 ^m +29° 46'	A2 5.71	1918 June 24	2,421,769.846	+39.4	Good	Y
				July 11	1,786.831	-10.9	"	
				Aug. 27	1,833.654	- 9.8	"	
				Sept. 20	1,857.672	+28.6	Fair	
67	Boss 4706 H.R. 6977	18 ^h 30.8 ^m +18° 07'	A 5.73	1918 June 26	2,421,771.890	-40.4	Good	P
				" 29	1,774.792	-36.5	"	
				July 21	1,796.766	-30.5	Fair	
				" 24	1,799.757	-22.8	Good	
				Oct. 13	1,880.607	- 7.1	"	
				" 15	1,882.634	+16.8	Fair	

No.	Star	R.A. 1900 Dec. 1900	Type Vis. Mag.	Date	Julian Day G.M.T.	Radial Velocity	Quality	Dis- coverer
68	Boss 4869 H.R. 7251	19 ^h 02.6 ^m +53° 14'	Ao 5.3	1918 May 20	2,421,734.972	-51.2	Fair	Y
				June 17	1,762.889	-25.3	Poor	
				July 16	1,791.890	-67.6	Fair	
				Sept. 5	1,842.707	-21.3	Good	
				1919 July 6	2,146.837	-14.7	"	
				" 30	2,170.793	+8.0	Fair	
				Aug. 10	2,181.741	-15.0	"	
				" 22	2,193.683	-31.5	"	
69	Boss 4870 H.R. 7258	19 ^h 03.1 ^m +41° 16'	A 6.15	1918 May 24	2,421,738.950	-36.7	Good	Y
				June 14	1,759.940	-15.0	"	
				" 17	1,762.840	-29.8	"	
				" 18	1,763.915	-32.6	"	
70	Boss 4876	19 ^h 04.4 ^m +38° 46'	A3 7.8	1919 June 17	2,422,127.914	+52.0	Fair	Y
				July 13	2,153.870	-4.2	"	
				" 23	2,163.825	-20.9	Weak	
				Aug. 6	2,177.773	-54.2	Fair	
				Sept. 22	2,224.658	-38.5	Weak	
71	Boss 4972 H.R. 7395	19 ^h 22.6 ^m +36° 07'	Aop 5.15	1918 June 26	2,421,771.902	-24.5	Good	P
				" 29	1,774.852	-25.8	"	
				July 6	1,781.816	-27.2	Fair	
				" 21	1,796.803	-17.1	Good	
				Oct. 24	1,891.647	-10.8	"	
				Dec. 15	1,943.569	-13.3	"	
72	Boss 4980 H.R. 7408	19 ^h 25.0 ^m +52° 07'	Ao 5.66	1918 Sept. 16	2,421,853.693	-1.6	Good	Y
				Oct. 11	1,878.642	-6.9	"	
				" 21	1,888.590	-7.3	"	
				1919 June 29	2,139.890	+14.6	"	
				July 27	2,167.811	+15.0	"	
				Aug. 22	2,193.693	+10.4	"	
				Oct. 2	2,234.607	+7.2	"	
73	Boss 5000 H.R. 7441	19 ^h 30.9 ^m +29° 14'	F5 5.42	1918 June 26	2,421,771.925	-9.5	Good	P
				" 29	1,774.852	-12.5	"	
				July 6	1,781.899	-9.6	"	
				" 27	1,802.842	-10.0	"	
				1919 June 26	2,136.907	-4.9	"	
				July 19	2,159.829	-2.3	"	
				Aug. 28	2,199.781	-7.9	"	
				Nov. 25	2,288.546	-40.2	"	
74	Boss 5026 H.R. 7484	19 ^h 36.4 ^m +54° 44'	F5 5.9	1919 July 21	2,422,161.798	$\begin{cases} -75.1 \\ +25.7 \end{cases}$	Good	H
				" 22	2,162.797	$\begin{cases} +106.0 \\ -125.1 \end{cases}$	"	
				" 23	2,163.854	-18.5	"	
75	Boss 5150 H.R. 7678	20 ^h 00.7 ^m +31° 56'	Bo 5.69	1918 June 18	2,421,763.944	+19.6	Good	Y
				July 11	1,786.849	+9.8	"	
				Aug. 5	1,811.828	+22.5	"	
				" 30	1,836.743	+25.0	"	
				Sept. 5	1,842.759	+21.3	"	

No.	Star	R.A. 1900 Dec. 1900	Type Vis. Mag.	Date	Julian Day G.M.T.	Radial Velocity	Quality	Dis- coverer	
76	Boss 5225	20 ^h 18.0 ^m	B9	1918 Oct. 13	2,421,880.649	-56.4	Fair	P	
	H.R. 7792	+61° 56'	5.6	" 19	1,886.611	-26.2	Good		
				" 24	1,891.660	-28.1	"		
				" 29	1,896.574	-47.2	"		
77	Boss 5236	20 ^h 20.0 ^m	B3	1918 June 28	2,421,773.923	-35.7	Fair	P	
	H.R. 7807	+37° 10'	5.68	Aug. 3	1,809.853	-43.0	Good		
				Oct. 15	1,882.668	-54.0	Fair		
				" 19	1,886.649	-44.5	Good		
78	Boss 5250	20 ^h 24.0 ^m	A0	1918 July 16	2,421,791.878	-17.7	Fair	Y	
	H.R. 7827	+56° 19'	6.21	" 30	1,805.817	-50.9	Good		
				1919 " 23	2,163.869	-16.1	Fair		
				Aug. 19	2,190.755	-16.5	Good		
79		21 ^h 00.3 ^m	A5	1918 Aug. 19	2,421,825.867	-41.9	Fair	P	
	H.R. 8074	+46° 29'	6.3	" 24	1,830.826	-13.3	"		
				" 25	1,831.854	+51.9 -69.7	Good		
				Sept. 15	1,852.742	-34.2			"
				Nov. 5	1,903.594	-7.5			"
80	Boss 5442	21 ^h 04.4 ^m	B8	1918 June 18	2,421,763.956	-10.8	Good	Y	
	H.R. 8094	+29° 48'	5.6	July 2	1,777.940	-47.5	"		
				" 11	1,786.907	-32.8	"		
				Aug. 30	1,836.793	-14.1	"		
81	Boss 5447	21 ^h 07.1 ^m	B9	1918 June 20	2,421,765.974	-20.7	Good	P	
	H.R. 8106	+53° 09'	5.7	Aug. 22	1,828.831	-32.4	"		
				" 24	1,830.796	-28.8	"		
				" 25	1,831.812	-30.3	"		
				Oct. 8	1,875.695	-25.2	"		
				" 29	1,896.626	-18.1	"		
				Nov. 5	1,903.608	-20.3	"		
				" 23	1,921.543	-16.0	"		
82		21 ^h 12.2 ^m	B5	1918 Aug. 23	2,421,829.775	-51.3	Fair	P	
	H.R. 8136	+47° 33'	6.32	" 24	1,830.847	-55.2	"		
				" 25	1,831.867	-62.1	"		
				Sept. 7	1,846.797	+0.5	Good		
				" 14	1,853.786	-7.6	"		
				" 15	1,854.758	-8.6	Poor		
83	Boss 5478	21 ^h 16.0 ^m	B5	1918 June 18	2,421,763.967	-22.8	Good	Y	
	H.R. 8161	+49° 06'	5.65	" 26	1,771.971	-25.0	"		
				July 11	1,786.917	-17.0	Poor		
				Sept. 13	1,850.702	-11.1	Good		
				Nov. 1	1,899.592	-26.7	"		
				1919 July 6	2,146.924	-39.6	"		
84		21 ^h 17.2 ^m	F8	1918 Aug. 23	2,421,829.826	-16.9	Good	P	
	H.R. 8170	+39° 55'	6.46	Oct. 8	1,875.713	+39.7	"		
				" 13	1,880.677	-47.3	"		
				" 19	1,886.677	+1.8	"		

No.	Star	R.A. 1900 Dec. 1900	Type Vis. Mag.	Date	Julian Day G.M.T.	Radial Velocity	Quality	Dis- coverer
85	Boss 5531 H.R. 8237	21 ^h 27.0 ^m +52° 31'	Ao 6.1	1918 July 16	2,421,791.908	-4.9	Good	Y
				" 30	1,805.831	-25.6	"	
				Oct. 30	1,897.619	-12.2	"	
				Dec. 16	1,944.545	-29.9	"	
				1919 Aug. 19	2,190.787	-18.9	"	
86	Boss 5579 H.R. 8300	21 ^h 38.4 ^m +40° 38'	Ao 5.5	1918 June 28	2,421,773.945	{ +69.8 -107.0 }	Good	Y
				July 16	1,791.921		Weak	
				Oct. 30	1,897.664	{ +22.3 -88.9 }	Good	
				Dec. 20	1,948.532	{ +77.3 -99.5 }	"	
				" 23	1,951.537	-24.5	"	
87	Boss 5620	21 ^h 46.8 ^m +66° 20'	F2 6.8	1919 Oct. 26	2,242,258.655	-44.5	Good	P'
				Nov. 7	2,270.654	+16.2	"	
88	H.R. 8422	28 ^h 01.8 ^m +44° 37'	Ao 6.4	1918 July 12	2,421,787.896	+1.7	Good	Y
				" 30	1,805.889	-1.5	"	
				Sept. 5	1,842.841	+9.6	Poor	
				Nov. 1	1,899.566	-23.6	Good	
				1919 Aug. 6	2,177.875	-13.3	"	
89	H.R. 8427	22 ^h 02.0 ^m +47° 45'	B3 6.2	1918 July 12	2,421,787.918	-143.0	Good	Y
				Aug. 5	1,811.876	-126.9	"	
				Sept. 16	1,853.747	+10.6	Weak	
				Nov. 4	1,902.676	-82.1	Good	
90	H.R. 8441	22 ^h 03.7 ^m +25° 03'	Fo 6.03	1918 July 12	2,421,787.931	-0.4	Good	Y
				Aug. 5	1,811.912	-7.3	"	
				Sept. 16	1,853.780	+6.7	"	
				Nov. 4	1,902.662	+1.3	"	
				1919 Jan. 8	1,967.550	-6.0	"	
91	Boss 5753	22 ^h 14.2 ^m +65° 38'	Ao 7.3	Aug. 27	2,198.845	+12.5	"	H
				1919 July 28	2,422,168.927	-31.0	Weak	
				Aug. 15	2,186.895	-22.0	Fair	
				" 18	2,189.903	-23.0	Weak	
				Sept. 12	2,214.830	+2.0	Fair	
92	Boss 5827 H.R. 8599	22 ^h 30.5 ^m +75° 43'	Ao 5.74	Oct. 3	2,235.723	± 0	"	P'
				1919 July 22	2,422,162.957	-36.7	Poor	
				Oct. 17	2,249.703	-2.7	Good	
93	Boss 5900 H.R. 8703	22 ^h 48.2 ^m +16° 19'	Ko 5.72	Dec. 2	2,295.606	-9.7	"	H
				1919 Sept. 9	2,422,211.845	+20.6	Good	
				" 15	2,217.786	-7.2	"	
				Oct. 3	2,235.762	+19.5	"	
94	Boss 5918 H.R. 8731	22 ^h 52.7 ^m +48° 09'	B3 5.2	" 13	2,245.766	-34.0	"	P
				1918 Oct. 8	2,421,875.752	-32.2	Good	
				" 13	1,880.723	+7.1	"	
				" 15	1,882.688	-5.4	"	
				" 19	1,886.691	-5.7	"	

No.	Star	R.A. 1900 Dec. 1900	Type Vis. Mag.	Date	Julian Day G.M.T.	Radial Velocity	Quality	Dis- coverer
95	H.R. 8800	23 ^h 02.7 ^m +45° 33'	B5 6.56	1918 July 16	2,421,791.968	-39.9	Fair	Y
				" 30	1,805.950	+25.5	"	
				Sept. 5	1,842.898	+49.2	"	
				Nov. 20	1,918.644	-57.9	Fine	
				Dec. 23	1,951.567	-128.7	Weak	
				1919 July 8	2,148.957	-43.8	Good	
96	H.R. 8803	23 ^h 03.0 ^m +59° 13'	B3 6.28	1918 Aug. 22	2,421,828.921	-14.8	Fair	P
				" 23	1,829.856	+15.6	Good	
				" 24	1,830.881	+71.8	"	
				Sept. 4	1,841.807	+21.2	Fair	
				" 14	1,851.812	+81.8	Good	
97	Boss 6034 H.R. 8913	23 ^h 22.3 ^m +42° 21'	B9 5.65	1918 Oct. 20	2,421,887.683	- 2.1	Fair	P
				" 24	1,891.710	- 7.1	Good	
				" 29	1,896.694	- 5.8	"	
				Nov. 5	1,903.635	-13.4	"	
				" 26	1,924.633	-22.0	"	
98	Boss 6070 H.R. 8960	23 ^h 32.6 ^m +16° 17'	A0 6.2	1918 Nov. 24	2,421,922.665	-13.3	Good	P
				" 30	1,928.610	-34.1	"	
				Dec. 15	1,943.623	- 1.8	"	
				" 29	1,957.624	-32.8	"	
99	Boss 6072 H.R. 8963	23 ^h 32.9 ^m +17° 51'	A0 5.4	1918 Nov. 24	2,421,922.678	-24.2	Good	P
				" 30	1,928.622	-39.8	"	
				Dec. 15	1,943.637	-36.8	"	
				" 15	1,943.647	-35.5	"	
				1919 Jan. 6	1,965.600	-16.6	Fair	
				" 6	1,965.608	- 5.1	Good	
100	Boss 6148 H.R. 9059	23 ^h 52.1 ^m +55° 09'	F5 5.69	1919 July 22	2,422,162.978	+34.7	Poor	P'
				Aug. 7	2,178.966	{ +62.6 } { -42.6 }	Fair	
				Oct. 15	2,247.778	{ +82.7 } { -57.6 }	"	

NOTES

- No. 1.—Boss 108—The lines in this spectrum are rather broad and not easy of measurement. The hydrogen lines are strong, but helium is weak, only 4472 being measurable and of about the same intensity and character as 4481 and K.
- No. 2.—Boss 282—This spectrum though containing numerous metallic lines is difficult of measurement as they are broad, diffuse and lacking in contrast. The measures in general depend chiefly on the hydrogen lines and on a strong though broad K and although the range is not great there is no doubt of its reality.
- No. 3.—Boss 283—This star of spectral type F8 and sharp lines was measured on the spectro-comparator and as in all stars of this type, the measures are reliable. This star and the preceding Boss 282 are separated by about $24''$ and evidently have a common proper motion as their distance and position angle have not appreciably changed in the last 80 years. Burnham discovered an eleventh magnitude companion to the fainter of the pair, Boss 283, which is distant about $0''.9$ and the measures of this close pair since then have shown, as he says, "that there is probably slow orbital motion." He further says:—"These three stars undoubtedly constitute a vast physical system."

The radial velocity measures of the wide pair show that this system is even more complicated than Burnham supposed, for the radial velocity of each varies, each is a spectroscopic binary and the system consists of five stars instead of three.

- No. 4.—Boss 307—The spectrum exhibits double lines on the plate taken October 28th. Eight lines of one component and seven due to the other were measured. When the lines are superimposed they are numerous and well defined, the type of spectrum being A5.
- No. 5.—H.R. 407—This spectrum of type F5 is of excellent quality for measurement, and the velocities obtained by the spectro-comparator are reliable.
- No. 6.—Boss 443 This spectrum is somewhat peculiar being rather of B8 type than A0 as both $\lambda 4471$ and $\lambda 4026$ are seen. On the second plate there appears to be emission between $\lambda 4471$ and $\lambda 4481$ but as it does not show on the other two plates too much reliance need not be placed upon it. The K line of calcium gives velocities different to those of the other, the velocities for the second and third plates being respectively $+31$ and $+5$.
- No. 7.—Boss 480—The hydrogen lines and the calcium K in this spectrum are strong and rather broad, but fairly well measurable. Numerous weak and rather broad metallic lines give fairly accordant results among themselves and agree with the values obtained from the hydrogen lines.
- Nos. 8 and 9.—Boss 497 —Both spectra are recorded for the brighter star. The component of the visual double is less than $4''$ distant and has a spectrum approximating A5. There is a suspicion that the spectrum of its component is also present and may be revealed on fine-grained plates. While the visual double is not classed as a binary according to Burnham the stars have a common proper motion of $0''.10$ and the determination of their spectroscopic orbits should prove interesting. It is hoped to investigate them here in the near future.

- No. 10.—Boss 606—In addition to the strong and rather broad hydrogen lines and K there are a number of fairly well defined metallic lines and as the measures exhibit good internal agreement, the velocities are reliable.
- No. 11.—H.R. 894—Hydrogen $H\gamma$ and $H\delta$ and the calcium K line and magnesium 4481 are all the lines measurable in this star. K and 4481 are narrow but faint. The hydrogen lines are rather broad but have a fairly sharp core. $H\beta$ shows double emission.
- No. 12.—Boss 787—This is a fine spectrum for measurement. There are very many narrow metallic lines in addition to a narrow K line and silicon 4128 and 4131.
- No. 13.—Boss 809—Numerous lines are present in the spectrum but they are not of very good quality for measurement. Additional plates will be obtained of this star to obtain the orbital elements.
- No. 14.—Boss 836—There are a number of fairly well defined metallic lines in this spectrum and these in addition to the hydrogen lines ensure fairly reliable velocity values.
- No. 15.—Boss 866—This spectrum of type A3 contains numerous metallic lines in addition to the hydrogen series but all the lines are broad and diffuse and the spectra are not susceptible of accurate measurement.
- No. 16.—Boss 943—The lines are unusually fine and narrow. 4128, 4131, K, $H\delta$, $H\gamma$, 4233, 4481 were all that were measured. The silicon lines are strong while K and 4481 are very faint but sharp.
- No. 17.—Boss 1004—The large number of metallic lines common to type F stars are, however, not as well defined as usual and are too broad to be suitable for measurement on the comparator. Measures of about 15 lines on each plate with the micrometer microscope exhibit good internal agreement.
- No. 18.—Boss 1013—There are many very fine lines on the spectrum of this star, from 16 to 20 being measured. The star is one of the Taurus cluster.
- No. 19.—Boss 1051—The quality of the spectrum for measurement is rather poor. There are numerous lines present which are rather fuzzy and poorly defined. This star belongs to the Taurus cluster.
- No. 20.—Boss 1058—The lines in this Fo spectrum are all broad and it is consequently unsuitable for measurement on the Hartmann Spectro-Comparator. The inter-agreement among the lines is fair, however, and the measures are reliable.
- No. 21.—Boss 1068—The spectrum of type B9 contains narrow and sharp Mg 4481 and K lines. The hydrogen lines are also well measurable but helium and silicon are weak. The measures may be considered as reliable.
- No. 22.—Boss 1085—Five lines were measured in the plates of this star. The hydrogen lines, calcium K and both 4471 and 4481. They are only of fair quality.
- No. 23.—Boss 1122—This spectrum listed Ao is nearer A2 and contains a large number of very sharp metallic lines and the measures are hence accurate.
- No. 24.—Boss 1244—This spectrum type A2 is very similar in character to No. 23 containing numerous narrow sharp metallic lines and the measures are equally reliable.
- No. 25.—Boss 1273—Spectrum much like that of No. 22. K is very faint and the other lines of not very good quality. 4471 was not measured.

- No. 26.—Boss 1276—The lines in this Ao spectrum are broad and faint, only 4481, K and the hydrogen lines being usually measurable. The inter-agreement among the lines is fair, however, and the measures probably of fair accuracy.
- No. 27.—Boss 1336—This star given as B9 in Harvard is, however, of somewhat earlier type as the helium lines are fairly strong, He, 4472 being of nearly equal intensity with Mg 4481. An average of 10 lines fairly well defined make the velocities obtained trustworthy. The magnitude given as 5.49 in Harvard must refer to the combined magnitudes of this and its companion No. 28, 10" away, as the magnitude of this star is nearer 6.5 than 5.5.
- No. 28.—Boss 1337—This star, of somewhat later type than the preceding, is not so suitable for accurate measurement as only the broad hydrogen lines and a narrow sharp K can be measured. However, the internal agreement is good, and there is no doubt of the reality of the variation as the change in position and the accuracy of the measurement of the sharp K is sufficient to establish this.
- This star and Boss 1336, each of which is a spectroscopic binary, are separated about $9''.5$ and are slowly approaching one another, their separation having diminished about $0''.4$ since 1831, at the rate of about $0''.5$ per century. It is of course not possible to say that they are physically connected, but owing to their similar types and magnitude and their comparative proximity in the sky, this is not improbable. This probability is strengthened by the fact that apparently the mean velocities, so far as can be determined from the few plates available, only differ slightly from one another.
- No. 29.—Boss 1369—The spectrum of this star is very similar to that of No. 16, and though the published range is rather small there is no doubt of the reality of the variation. 4233 was not measured.
- No. 30.—Boss 1410—This spectrum A2 is very similar in character to Nos. 15 and 26 and the measures of about the same order of accuracy.
- No. 31.—Boss 1452—This spectrum of type Ao contains in addition to the hydrogen lines and a trace of the silicon pair 4128, 4131, several metallic lines fairly well defined and the measures may be considered fairly reliable.
- No. 32.—Boss 1455—From 6 to 9 lines were measured in these spectra. Calcium K, the hydrogen lines H δ and H γ , also λ 4233 and 4481. There are traces of many faint metallic lines which agree in wave length with lines in the spectrum of α Cygni. All are sharp and narrow. The silicon lines 4128 and 4131 are also present.
- No. 33.—Boss 1559—Numerous lines characteristic of this type of spectrum are present in the spectrum. They are of fair quality only. From 11 to 14 were measured.
- No. 34.—Boss 1714—This star of type Ao has besides the hydrogen series and K only at the most three or four measurable metallic lines which are generally rather broad and the measures are hence not of the highest accuracy. Experience of similar type constant velocity stars would indicate a plate error of about 3 km.
- No. 35.—Boss 2013—The calcium line K, the Hydrogen lines H δ and H γ and the two lines λ 4481 and 4549 were all that were measured in this spectrum. They are fairly well defined and narrow. K, 4481 and 4549 are rather weak for accurate measurement.

- No. 36.—Boss 2022—The lines in this Ao spectrum are all very broad and the plates are hence not susceptible of accurate measurement.
- No. 37.—Boss 2142—The spectrum consists of broad hydrogen lines with sharp magnesium, $\lambda 4481$ and sharp calcium $\lambda 3933$. The second plate shows the hydrogen lines apparently complex and the calcium and magnesium decidedly so. The third, fourth and fifth velocities must be close to the velocity of the system as the latter two lines are extremely sharp.
- No. 38.—Boss 2173—The lines are of good quality for measurement. The silicon lines 4128, 4131 are strong. The calcium, hydrogen and magnesium and several iron lines are also well defined.
- No. 39.—Boss 2251—From 8 to 14 lines were measured in the spectra of this star. They are of poor quality. There seems little doubt of the reality of the variation but the computation of an orbit would prove a difficult task if the range is not larger than indicated.
- No. 40.—Boss 2432—The lines in this F5 spectrum are broad and though numerous, few are well enough defined for accurate measurements. The measures are fairly reliable.
- No. 41.—Boss 2463—This is a fine spectrum for accurate measurement, being very similar to Procyon. The measures were made on the Hartmann engine with Procyon as a standard.
- No. 42.—Boss 2634—In the first plate obtained and measured on the spectro-comparator the lines are beautifully sharp. In the other three plates they are broad and diffuse showing distinctly doubled on one plate and had to be measured with the micrometer microscope.
- No. 43.—Boss 2672—The relative intensity of the hydrogen and calcium lines would place this star in class Ao but helium 4026 was measured on one plate and appears on others. Usually only $H\gamma$, $H\delta$, 4481 and K are measured.
- No. 44.—Boss 2951—Numerous metallic lines are present in the spectrum of this star but they are not of the best quality for measurement. Announced spectroscopic binary by Adams, A. S. P., June, 1915.
- No. 45.—Boss 3102—The lines in this F8 star are well defined and all the plates were measured in the spectro-comparator. The probable error of a single plate is hence not likely greater than one kilometre per second.
- No. 46.—Boss 3354—The spectrum though listed as Ao is more nearly B9 as the silicon pair 4128, 4131 are well marked and K is very narrow. Several well defined metallic lines are present and the doubled spectrum with components of nearly equal intensity permits of fairly accurate measurement.
- No. 47.—Boss 3555—Three of the four spectra taken of this star show a typical F5 type and were measured on the Hartmann comparator. The plate taken April 11 shows doubled lines.
- No. 48.—Boss 3652—This is the fainter star of the double No. 6778 in Burnham's General Catalogue. It shows a small range. The estimated V_o would be about -24.0 km. The brighter star has a measured velocity of -38.6 km. L.O.B., 229.
- No. 49.—Boss 3674—The first four plates of this star show the calcium line K, the hydrogen series and 4481. There are traces of many faint rather poor lines. The last three plates show the metallic lines fairly sharp and measureable. The spectrum may be composite.

- No. 50.—Boss 3909—In addition to the hydrogen lines the magnesium $\lambda 4481$ and calcium $\lambda 3933$ are fairly sharp and numerous metallic lines also appear. On the best plates 10 or 12 lines were measured, on the weak ones only 3 or 4, but there seems no doubt of a real variation in velocity.
- No. 51.—Boss 4098—Calcium K, hydrogen lines $H\delta$, $H\gamma$, $H\beta$, and the magnesium line $\lambda 4481$ were measured in the spectrum of this star. There are indications of numerous rather broad metallic lines showing on the plates. Magnesium $\lambda 4481$ is very faint in comparison with the calcium K. The hydrogen lines are fairly well defined.
- No. 52.—Boss 4121—The calcium line K, $\lambda 4481$ and $\lambda 4549$, together with the two hydrogen lines $H\delta$ and $H\gamma$ were all that were measured in these spectra. The lines are not of very good quality for accurate measurement.
- No. 53.—Boss 4123—This spectrum, given as A in H.R., is approximately A2 as judged by the relative intensity of K and the H lines. The spectrum is composite and in consequence the lines generally are very broad and diffuse. In the last plate, where the components are separated by about 140 km., there are a number of metallic lines present but otherwise only the hydrogen, $\lambda 4481$, mg., and K are measureable.
- No. 54.—H.R. 6169—There are a few good lines in the spectrum of this star. K, $\lambda 4481$, H and $\lambda 4549$, also many metallic lines can be seen faint and narrow.
- No. 55.—H.R. 6385—This is a fine spectrum for accurate measurement. There are very many fine lines present and the range shown by the measures is quite large.
- No. 56.—Boss 4411—This well defined F8 spectrum was measured on the comparator. The two plates of 1918 did not indicate variation and four plates were obtained in 1919 before any were measured although the first one would have been sufficient to show its binary character.
- No. 57.—Boss 4499—The hydrogen lines and calcium K are exceptionally strong and well defined. Mg. $\lambda 4481$ is faint but well defined.
- No. 58.—Boss 4507—The hydrogen lines are quite well defined in this star which has in addition numerous metallic lines found in this type, from 12 to 20 of which were measured on each plate. The orbit of this star has been completed.
- No. 59.—H.R. 6767—There are many rather ill-defined lines in the spectrum of this star, which look of fair quality under the low magnifying power of an eyepiece, but which are very difficult to set on under the microscope of the measuring engine.
- No. 60.—Boss 4602—This spectrum, classified as F5, is more nearly solar type and is of good quality for measurement. The plates were measured on the Hartmann Spectro-Comparator. As measures of constant velocity solar type stars, with this engine, show that the probable error of a plate is well under 1 km. per sec. these velocities are probably equally accurate.
- No. 61.—H.R. 6814—The hydrogen lines and calcium K are broad but fairly well measurable. A few metallic lines show but with the exception of Mg $\lambda 4481$ they are very diffuse and unreliable.
- No. 62.—Boss 4614—The hydrogen lines, together with a very faint calcium line and a faint magnesium, are all that were seen in the spectrum. The definition of the hydrogen lines is fair and the accordance of the velocities from the various lines very good.

- No. 63. Boss 4622—The first plate showed definite double lines of the numerous metallic ones found in spectra of this type though none of them are very sharp.
- No. 64. Boss 4644—The numerous metallic lines in this spectrum are weak, broad and unsuitable for accurate measurement. The hydrogen lines, 4481 and K, are, however, strong, fairly well defined and agree well among themselves so that the resulting velocity values may be considered reasonably reliable.
- No. 65.—Boss 4661—The spectrum of this star is very much like that of star No. 1 save that there are practically no indications of faint metallic lines.
- No. 66. Boss 4669—Numerous fine metallic lines are present in the spectrum thirteen to fifteen of which were measured. The type might be listed as A5 rather than type A. The hydrogen series and calcium K lines are also sharply defined.

Dr. W. S. Adams has kindly drawn our attention to the fact that this star was contained in a list of binaries discovered at Mt. Wilson and announced in the Publications of the Astronomical Society of the Pacific. Its orbit has now been computed and published in the Journal of the R.A.S.C. and also in the Dominion Astrophysical Observatory Publications, Vol. 1, No. 6.

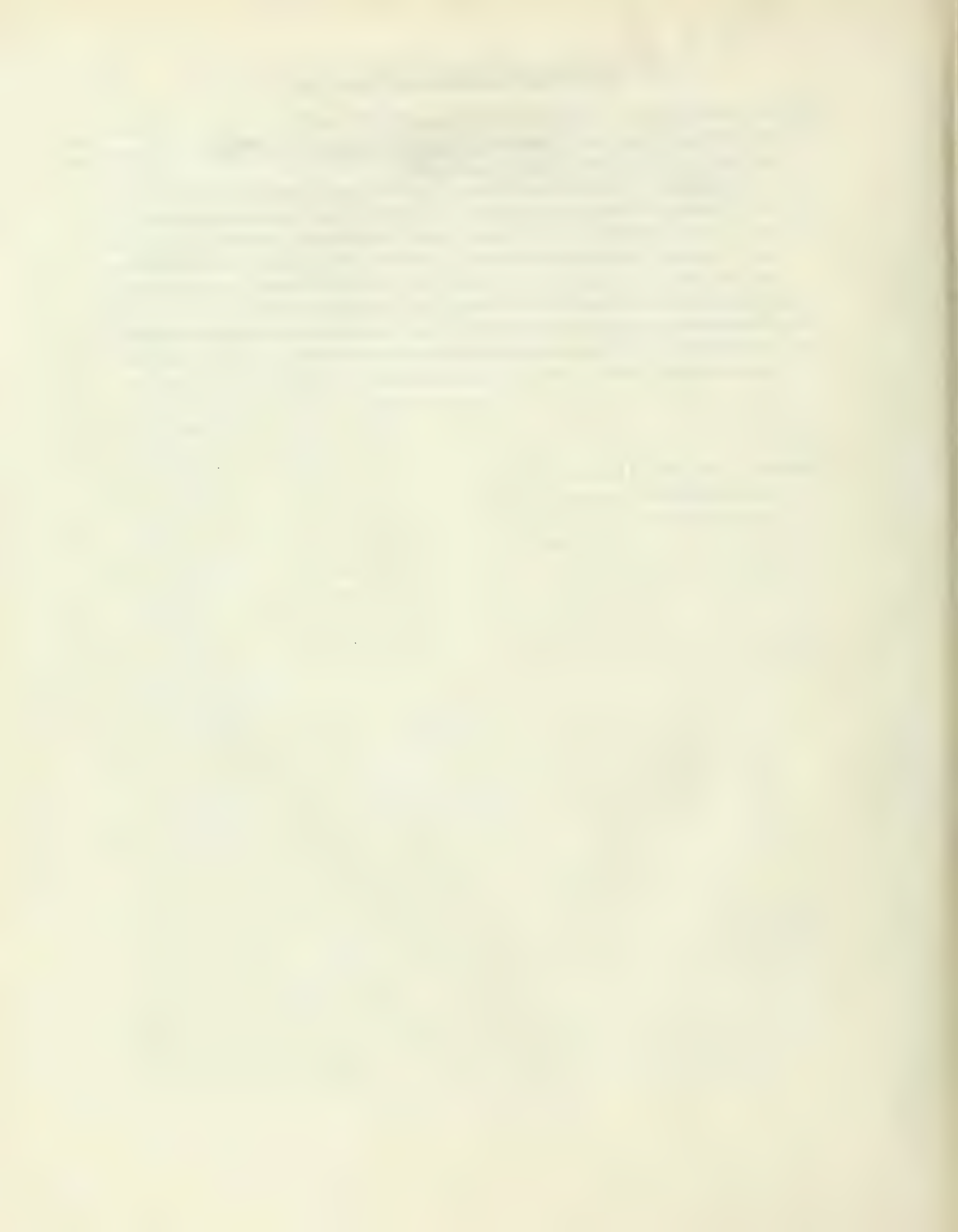
- No. 67.—Boss 4706—The hydrogen lines $H\delta$, $H\gamma$, $H\beta$, although broad and intense in this star, are fairly well measurable. Mg. $\lambda 4481$ is the best measurable line, and in some plates one or two other metallic lines which are all faint were measured. The spectral type is approximately A2.
- No. 68.—Boss 4869—This is a rather difficult spectrum to measure. The calcium line K and $\lambda 4481$ together with the hydrogen lines are present. They are rather wide and diffuse and often suggest duplicity.
- No. 69.—Boss 4870—This star is given as A type in H.R. but it is really B2 type with sharp helium and silicon lines showing. The calcium K line is sharp and narrow and the measures on six of the plates indicate that it may exhibit a somewhat smaller range than the other lines present in the spectrum.
- No. 70.—Boss 4876—This is a good spectrum for measurement and the range is over 100 kms. but the faintness of the star would make a determination of the elements difficult for any but the largest telescopes.
- No. 71.—Boss 4972—This spectrum contains numerous good lines for measurement, the best being the hydrogen series, which, though strong, have sharply defined edges. The line 4481 is good, K especially sharp, the silicon pair, 4128, 4131, stand out very prominently and probably form the "peculiar" character of the spectrum.
- No. 72.—Boss 4980—Several good lines are present in this spectrum. K and 4481 are both sharp, and the hydrogen series is also very good. The measures indicate a very long period as all the plates taken the first year are negative and those in the next season positive.
- No. 73.—Boss 5000—In this F5 spectrum, measured on the spectro-comparator, as in Boss 4411, the four plates measured in 1918 had less than 3 km range and it was only when the last plate was measured that its binary character became certain. The orbit is probably highly eccentric with the longitude of the apse nearly 180° .

- No. 74.—Boss 5026—The spectra of both components are present, the intensities being very nearly the same for each. The star's orbit has been determined from additional observations made here.
- No. 75.—Boss 5150—This star promises a very interesting spectrum. The velocities given in the table result from helium and silicon lines. The hydrogen lines give about the same or larger range, but are at least ten kilometers more negative. The calcium K line is about thirty kilometers to the violet and seems to give a constant velocity. For the five plates in order the hydrogen lines give $+9.4$, -2.6 , $+0.6$, $+11.5$, -17.1 , km., and the calcium lines -10.3 , -12.3 , -11.7 , -8.5 , -8.3 km. The lines are of good quality.
- We find that it has been announced as a binary previously by W. S. Adams in the Publications of the Astronomical Society of the Pacific, December 1917.
- No. 76.—Boss 5225—Hydrogen and 4481 are the best lines in this spectrum and the measures depend on these lines. K is broad and rather weak and a few faint, broad metallic lines are visible.
- No. 77.—Boss 5236—This star classified as A, is undoubtedly an early B type and is peculiar in having very broad helium and hydrogen lines of low contrast and a narrow sharp calcium K which gives a smaller range than the broad lines. Both spectra show on two of the plates and on the last K is doubled as well as some of the diffuse lines.
- No. 78.—Boss 5250—The spectrum of this star is very much the same as No. 62, the calcium K line being, however, much stronger.
- No. 79.—H.R. 8074—Although the hydrogen and metallic lines in this spectrum are broad, the measures generally are in good agreement. The second spectrum was measured on one plate and its presence probably accounts for the width of the lines.
- No. 80.—Boss 5442—This star is listed in Harvard as of type Ao. The helium lines are quite measurable on the spectrograms taken here, and the silicon lines 4128 and 4131 are prominent. The calcium line K seems to give a smaller range than do the other lines. The spectrum is of good quality for measurement.
- No. 81.—Boss 5447—Besides the hydrogen lines, which, though strong, are sharply defined, and the sharp silicon pair 4128, 4131, this spectrum contains numerous well defined metallic lines and is well suited for accurate measurement. Although the range of velocity is small, measures of similar constant velocity stars indicate its undoubted reality.
- No. 82.—H.R. 8136—The lines are broad and diffuse with the exception of calcium K. Mg. $\lambda 4481$ is faint and not measurable on all the plates. The spectrum is probably composite as the helium lines on one plate indicate doubling.
- No. 83.—Boss 5478—The lines in the spectrum of this star are rather poor. K is almost invisible. The helium lines 4026 and 4471 are fair and the hydrogen lines are also measurable, 4481 is fair. The determination of orbital elements would be rather difficult unless the range is larger than indicated.

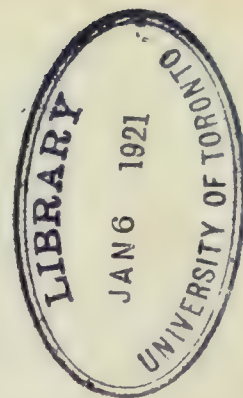
- No. 84.—H.R. 8170—This spectrum is of excellent quality for measurement, about midway between Procyon and the sun in type, and the plates were measured on the Hartmann Comparator. The elements of the orbit of this star have been obtained since its discovery and have been published in Vol. 1, No. 3 of this publication.
- No. 85.—Boss 5531—The spectrum is rather peculiar in the great intensity of the calcium K line in comparison to the hydrogen lines and the magnesium line 4481. Besides these lines, which are fairly well defined, there are traces of many faint lines in the spectrum not suitable for measurement.
- No. 86.—Boss 5579—The measures of this star rest on the calcium K line alone. The two components are of about equal intensity and it is not possible to distinguish between them on the three plates. The hydrogen lines are rather wide and on none of the plates could they be measured as double.
- No. 87.—Boss 5620—This is a good spectrum for measurement. Numerous metallic lines and H δ and H γ give very accordant results.
- No. 88.—H.R. 8422—Hydrogen, calcium, magnesium lines are all that were measured in the spectrum. They are of fair quality.
- No. 89.—H.R. 8427—The usual lines of a star of this type are present in the spectrum. They are of rather poor quality. The calcium K line gives apparently a constant or nearly constant velocity. An orbit has since been completed for this star.
- No. 90.—H.R. 8441—The lines are rather diffuse and while very many are present the interagreement of the measures is not very good. There can be very little doubt, however, of the reality of a small variation in the velocity.
- No. 91.—Boss 5753—The hydrogen lines are rather broad for accurate measurement but the magnesium line λ 4481 is good and there seems no reasonable doubt of a real variation in velocity.
- No. 92.—Boss 5827—Hydrogen, calcium and magnesium lines were the only ones measured in this spectrum. They are of fair quality.
- No. 93.—Boss 5900—Other measures have since been made and it is hoped to investigate the star's orbit shortly. The measures were made on the spectro-comparator.
- No. 94.—Boss 5918—This spectrum is similar to that of No. 77 and in addition calcium H is sometimes separated from H ϵ , and H and K give a smaller range than the helium and hydrogen lines. Spectrum possibly double.
- The values of the velocity published in the Journal R.A.S.C. for this star are slightly in error owing to an error in the correction to sun.
- No. 95.—H.R. 8800—On the majority of the plates of this star only H γ and 4388 and 4471 were measurable. But on the plate taken November 20 the usual helium lines 4026, 4144 are also quite measurable. The calcium K line was measured on two plates and yields a constant velocity.
- No. 96.—H.R. 8803—This spectrum is very suitable for accurate measurement, containing good helium, silicon, calcium, magnesium and hydrogen lines, it is also peculiar in the smaller range given by calcium. On two of the plates one or two of the lines give indications of doubling.

- No. 97.—Boss 6034—The hydrogen lines in this spectrum, though broad, are well measurable, 4481 and K are well defined, and numerous faint but sharp metallic lines make this spectrum suited for accurate measurement.
- No. 98.—Boss 6070—This star has beautifully narrow sharp metallic lines in addition to the hydrogen series and the measures are hence very satisfactory and reliable.
- No. 99.—Boss 6072—This star of the same type as the preceding has only the hydrogen series, Mg 4481 and K measurable, and all of them are rather broad. Although the two last plates do not agree very closely, the internal agreement among the lines in the several plates is sufficient to establish the variable velocity.
- No. 100.—Boss 6143—The spectrum shows double lines on the plates taken on August 7 and October 15. 9 lines of each component were measured. The lines are sharp. When superimposed the lines are not so well defined.

Dominion Astrophysical Observatory,
Victoria, B.C.,
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THE SPECTROSCOPIC ORBIT OF U CORONAE

BY J. S. PLASKETT

The eclipsing variable U Coronae, R.A. $15^h 14.1^m$, Dec. $32^\circ 1'$ (1900), mag. 7.5, type B3 was placed under observation for the purpose of determining the spectroscopic orbit and hence the dimensions of the system on Mar. 25, 1919. Nine spectra were obtained and measured during the season but press of other work and some peculiarities in the measures and results led to the postponement of its completion until 1920. Owing to the diffuse character of the spectral lines the measures were ragged and moreover the spectroscopic and photometric phases did not agree. In addition the spectrum of the faint component, which according to the photometric orbits should not be visible, was measured with certainty on four of these plates. These peculiarities, however, increased the interest in the orbit and observations were renewed on Feb. 27, 1920, and ten additional plates were obtained, the last on May 5.

On comparing the initial phase of the photometric orbit as given by Shapley¹, which was used in the work of 1919, with the observations of Wendell², it was found there must have been a misprint or error in the initial epoch given by the former. Upon using Wendell's values the discrepancy between photometric and spectroscopic phases disappeared. However, the spectra of 1920 fully confirmed the presence of the second component and it was measured on six of the ten plates of 1920. Although the lines of the second spectrum are faint and difficult to set upon nearly as many were measured as of the primary, there was fair interagreement and the probable error per plate was not much higher. It appears that the secondary minimum had not been observed by Wendell, and that Shapley in obtaining the photometric orbit made five different assumptions as to the relative light of the fainter star varying between zero and twenty-six per cent of the total light of the system. As it is generally assumed that the second spectrum will not appear if there is a greater difference than one magnitude between the components, it is apparent that all these assumptions give too small a proportion of the total light to the fainter body and that the secondary minimum should be carefully observed in order to correct the photometric orbit.

¹Contributions from Princeton Observatory, No. 3, page 17.

²Harvard Annals, 69, page 76.

The spectra of the two components of U Coronae appear to be of the same type, approximately B3 and the lines measured were $H\gamma$, $H\delta$; Helium 4472, 4388, 4144, 4026; carbon 4267; magnesium 4481; calcium 3934. All the lines are broad, diffuse, lacking in contrast and difficult to accurately measure, with the result that the residuals of single plates are frequently high. Most of the plates were twice measured differing in two or three cases by 20 to 40 kms. The mean of these duplicate measures was used, weighted in two cases where one of the measures appeared more reliable than the other.

Two of the plates were discarded, one as being too weak and the other as affected by blending of the spectra and the measures of the seventeen spectra used in determining the orbit are given in the table below with the date, phase, velocities and residuals from the final orbit.

OBSERVATIONS OF U CORONAE

Plate Number	Date	Julian Date	Phase	Velocity		Residual (O-C)	
				Bright	Faint	Bright	Faint
1704	Mar. 25, 1919.	2,412,043.924	0.137	-45.7	.....	-21.0	
1742	Apr. 1	050.949	0.258	-49.1	.....	-10.1	
1803	" 13	062.919	1.872	+19.5		+ 8.8	
1886	" 26	075.926	1.069	-39.1	+139.9	-33.1	-21.9
1910	" 29	078.951	0.612	-67.7	+144.7	+ 3.8	-15.2
1940	May 3	082.941	1.180	-51.8	+131.0	+14.3	+13.0
1984	" 6	085.912	0.698	-76.0	+174.7	- 2.0	+ 7.4
2234	July 1	141.744	1.295	-66.6	+136.6	- 9.9	+15.6
2320	" 9	149.715	2.362	+55.3	-167.5	- 0.8	+ 7.6
3940	Mar. 16, 1920.	400.981	1.614	-22.4		- 0.8	
3944	" 17	401.074	1.707	-26.3		-16.4	
4011	Apr. 5	420.867	0.787	-76.8	+166.8	- 0.4	- 5.8
4029	" 7	422.899	2.819	+63.8	-202.1	+ 7.8	-28.3
4120	" 22	437.806	0.565	-64.2	+178.4	+ 2.9	+30.1
4156	" 24	439.912	2.571	+61.7	-185.4	- 0.3	+ 4.0
4172	" 27	442.923	2.129	+51.6	-120.5	+12.6	+ 8.8
4238	May 5	450.744	3.045	+41.5	-142.6	+ 2.1	-12.0

These observations were combined as below to form nine normal places consisting of one place (No. 4) of three rather poor plates, six places of two plates each and two places of one plate each. The maximum separation of phase in any normal place being less than a quarter day.

NORMAL PLACES

Number	Weight	Phase	Velocity		Residual (Prel.)		Residual (Corr'd.)	
			Bright	Faint	Bright	Faint	Bright	Faint
1	2	0.198	-47.4	.....	-15.7	.....	-15.4	.....
2	2	0.604	-66.0	+161.6	+ 3.4	+ 5.6	+ 3.4	+ 7.0
3	2	0.742	-76.4	+170.8	- 1.1	- 0.8	- 1.1	+ 0.7
4	2	1.181	-52.5	+135.8	+13.1	-10.4	+13.2	- 9.1
5	2	1.660	-24.4	.....	- 9.0	.....	- 8.6	.....
6	1	1.872	+19.5	.....	+ 8.1	.....	+ 8.7	.....
7	2	2.246	+53.4	-144.0	+ 3.6	+11.4	+ 4.5	+11.1
8	2	2.695	+62.8	-193.8	+ 1.1	- 7.2	+ 2.1	- 7.7
9	1	3.045	+41.5	-142.6	+ 1.2	-12.0	+ 2.1	-12.3

These normal places were plotted as usual, a circular orbit as given by the photometric solution was assumed, and the amplitude and velocity of the system determined graphically. Spectroscopic and photometric phases evidently agreed so closely that in view of the uncertainty of the measures and their position, generally near the maximum and minimum velocities, it was useless to apply a correction for phase. The preliminary elements assumed were

$$\gamma \text{ velocity of system} = -7.0 \text{ km. per sec.}$$

$$K_1 \text{ semi-amplitude bright star} = 70 \text{ km.}$$

$$K_2 \text{ semi-amplitude faint star} = 183 \text{ km.}$$

The normal equations become

$$13.50\delta\gamma - 1.150\delta K_1 + .742\delta K_2 = -6.65$$

$$+ 4.338\delta K_1 = -1.54$$

$$+ 4.182\delta K_2 = -4.72$$

whose solutions gave the values

$$\delta\gamma = -0.48$$

$$\gamma = -7.5 \pm 1.7$$

$$\delta K_1 = -0.51$$

$$K_1 = 69.5 \pm 3.1$$

$$\delta K_2 = -1.04$$

$$K_2 = 181.9 \pm 4.2$$

The probable error of a single plate for the bright star is ± 8.5 km. for the faint ± 11.4 .

It is very doubtful whether this solution is any improvement over the preliminary values for although some of the higher residuals are slightly reduced this is at the expense of an increase of the smaller residuals, the sum of the squares remaining practically unchanged. This result is due of course to the greater effect of the high residuals in changing the form of orbit in a least squares solution. However, the ratio of the masses remains practically unaltered and there is little difference in the final dimensions of the system which may be deemed practically correct.

In view of the appearance of the second spectrum, the choice of the five photometric solutions given by Shapley¹ should evidently be No. 4, the one in which the faint component is assumed to have the greatest brightness, twenty-six per cent of the light of the system.

From this photometric orbit we have the inclination of the orbit plane $81^\circ 23'$ and the radii of the bright and faint components .167 and .273 respectively of their separation.

From the spectroscopic orbit we have a $\sin i = 11,940,000$ hence $a = 12,080,000$ km. $= 17.36\odot$ $(m_1 + m_2) \sin^3 i = 5.7\odot$ hence $m_1 + m_2 = 5.90\odot$

Hence combining photometric and spectroscopic data we obtain

$$\text{Semi axis major bright star } a_b = 3,339,000 \text{ km.} = 4.80\odot$$

$$\text{Semi axis major faint star } a_f = 8,741,000 \text{ km.} = 12.56$$

$$\text{Radius bright star } r_b = 2,017,000 \text{ km.} = 2.90$$

$$\text{Radius faint star } r_f = 3,298,000 \text{ km.} = 4.74$$

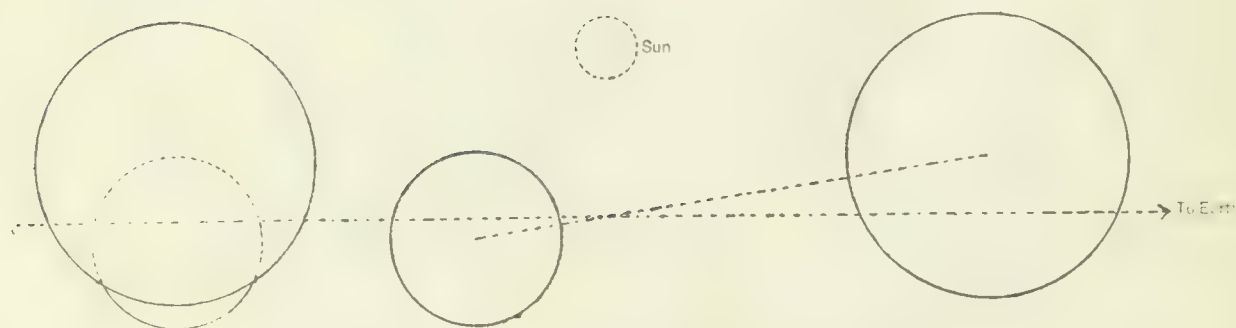
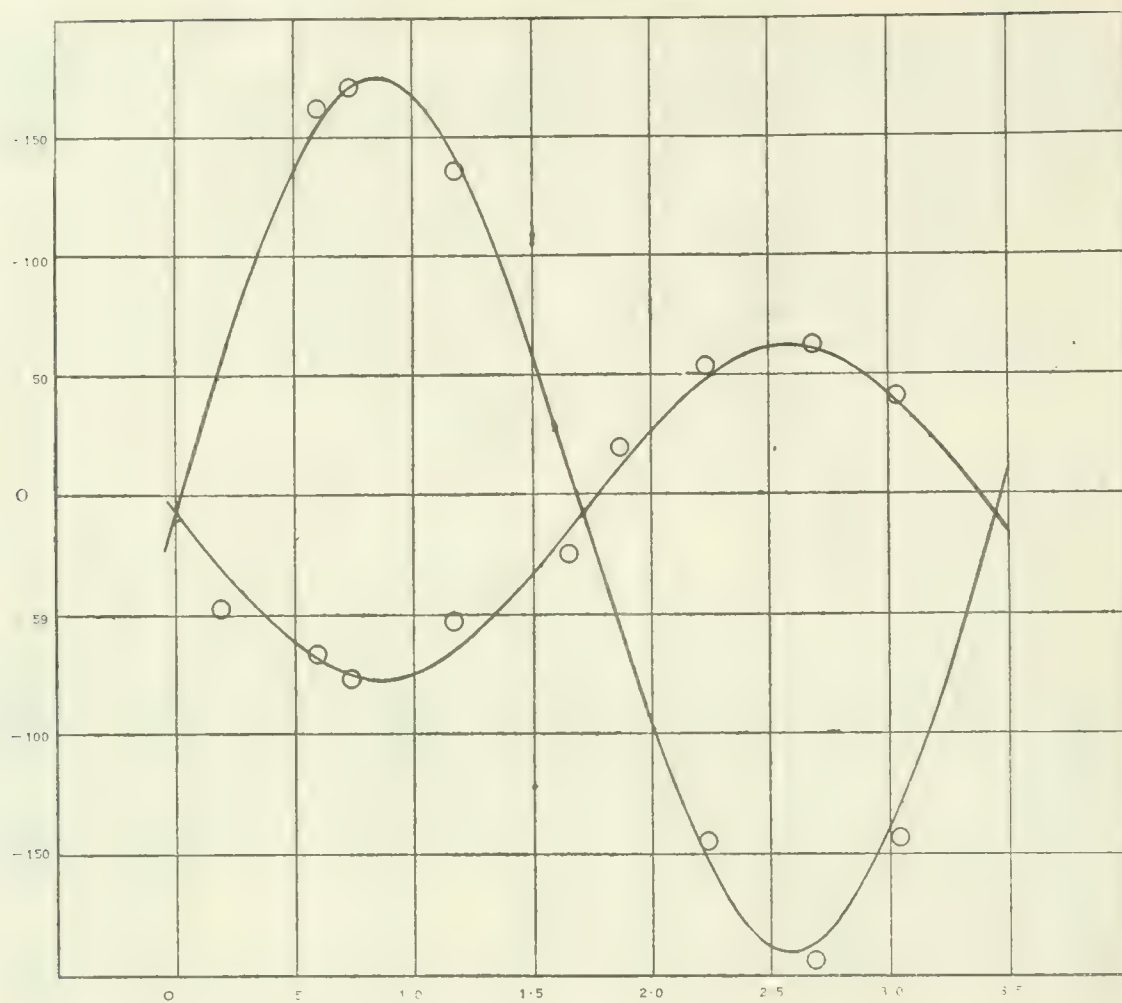
$$\text{Mass bright star } m_b = 4.27$$

$$\text{Mass faint star } m_f = 1.63$$

$$\text{Density bright star } \rho_b = .175$$

$$\text{Density faint star } \rho_f = .015$$

¹ Contributions from Princeton Observatory, No. 3, p. 86.



Velocity Curve and Relative Dimensions of U Coronae.

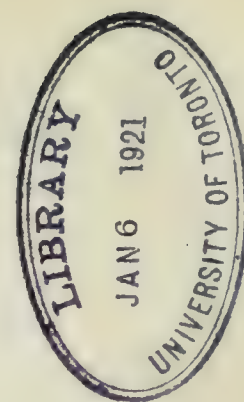
If we assume according to Shapley¹ the surface intensity of a B3 star to be -2.7 magnitudes as compared with the sun whose absolute magnitude is taken as 4.86 , the absolute magnitude of the bright component of U Coronae whose apparent magnitude is 7.85 is -0.15 and the parallax is $0''.0025$. It is worth mentioning, however, that the faint component is also of spectrum B3 while its surface intensity is only about one-eighth as great. The brightness per unit surface is perhaps also a function of the density and it is evident that too much weight should not be placed on the parallax thus determined though it is likely of the right order.

Although the character of the lines in both spectra is such as to prevent accurate measures, still the range of velocity is so great as to ensure fairly accurate relative values and elements. The dimensions of the system, so far as the spectroscopic orbit is concerned, are probably correct within five per cent. The figure shows the velocity curves of the two components with the normal places plotted as circles and, below, the relative dimensions of the system as compared with the sun.

Dominion Astrophysical Observatory,
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June, 1920.

¹ Ap. J. 40, p. 415.

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ORBIT OF THE SPECTROSCOPIC BINARY H.R. 8427

BY REYNOLD K. YOUNG

The binary character of the star, R.A. (1900) 22^h 02^m.0, Dec. +47° 45', Mag. 6.2, was announced by the writer in 1919. At that time it was noticed that the H and K lines of Calcium seemed to give nearly constant velocities and further observations have been made to investigate this and to determine the orbital elements.

The spectrum is classified as of type A in the Revised Harvard Photometry, Volume 50 but the later Draper Catalogue gives it as B3. The spectra taken here seem to show approximately the latter type or possibly B2, for the carbon line 4267 is quite strong. The lines are of rather poor quality and the Calcium lines, usually so sharp and narrow in spectra where they do not shift with the other lines, are not very good. They are, however, better than the other lines. The velocities resulting from them are not included in the mean. In the table of 32 observations below they are listed under the heading "K line". In general the K line alone was measured, but sometimes when the shift of the neighbouring H ϵ line permitted, the H line could be measured also and in these cases the given velocity is the mean of the two lines.

OBSERVATIONS OF H.R. 8427

Plate	Date	Julian Date G.M.T.	Phase	Velocity	Lines	Wt.	K Line	Residuals O-C
1918								
348	July 12.	2,421,787.918	1.81	-143.0	5		- 1.3	+ 2.0
438	Aug. 5.	1,811.876	1.88	-126.9	6		- 3.0	+14.1
624	Sept. 16.	1,853.747	0.30	+ 10.6	2		+32.3	-18.4
848	Nov. 4.	1,902.676	1.45	- 82.1	6	1	+ 6.7	+ 1.9
1919								
2151	June 17.	2,127.954	0.812	+116.1	6	1	- 3.5	+14.1
2201	" 28.	2,138.950	0.950	+ 81.7	6	1	+40.8	+ 1.7
2215	" 29.	2,139.948	1.948	-140.5	7	1	- 2.1	- 9.0
2231	" 30.	2,140.953	0.782	+100.4	6	1	+ 2.5	+ 5.6
2246	July 1.	2,141.952	1.781	-166.2	5	1	+ 8.8	-21.0
2260	" 2.	2,142.955	0.613	+ 93.8	7	1	+ 1.2	-10.0
2272	" 3.	2,143.945	1.603	-129.6	6	1	-13.4	- 5.6
2287	" 6	2,146.948	0.261	+ 10.2	6	1	- 5.6	- 3.8
2304	" 7.	2,147.960	1.273	-25.7	6	1	+ 2.2	- 3.7
2318	" 8.	2,148.936	0.079	- 39.9	6	1	+ 0.2	+14.0
2330	" 9.	2,149.890	1.033	+ 41.5	5	1	+ 7.5	-17.5
2334	" 9.	2,149.961	1.104	+ 27.9	6	1	- 1.5	- 7.0
2359	" 13.	2,153.943	0.743	+116.9	4	1	+ 5.2	+ 9.0

Plate	Date	Julian Date G.M.T.	Phase	Velocity	Lines	Wt.	K Line	Residuals O-C
1919								
2394	July 15.....	2,155.945	0.571	+101.0	4	1	+ 8.1	+ 1.0
2430	" 18.....	2,158.922	1.379	- 51.6	6	1	+ 2.1	+10.4
2444	" 19.....	2,159.957	0.242	+ 0.6	6	1	+ 4.1	- 7.0
2462	" 20.....	2,160.940	1.225	- 6.2	8	1	- 1.0	0.0
2481	" 21.....	2,161.966	0.080	- 44.3	6	1	+12.2	+ 6.7
2500	" 22.....	2,162.947	1.061	+ 68.9	6	1	- 0.3	+19.0
2520	" 23.....	2,163.939	2.053	-123.4	5	1	+ 6.5	-11.4
2565	" 28.....	2,168.904	0.493	+ 90.6	3	1		+ 5.6
2592	" 30.....	2,170.960	0.377	+ 54.9	4	1	- 3.5	- 1.0
2619	Aug. 7.....	2,178.908	1.808	-141.0	5	1	-17.4	+ 4.0
2631	" 9.....	2,422,180.899	1.627	-128.0	5	1	+ 0.9	+ 1.0
2809	" 22.....	2,193.864	1.559	- 99.4	5	1	+20.0	+15.6
2865	" 29.....	2,200.832	2.010	-132.5	5	1	+ 4.1	-11.0
2912	Sept. 9.....	2,211.774	2.091	- 96.0	6	1	- 0.3	+ 6.0
2913	" 9.....	2,422,211.788	2.105	- 79.4	5	$\frac{1}{2}$	+ 1.1	+18.6

The observations extend over an interval of 424 days, four plates being taken in 1918 and the remainder in 1919. The earlier plates were made use of only in determining the period. This was fixed at 2.1722 days and not included in a least-squares solution made for the elements. It sometimes happens that a period determined in this way needs to be modified slightly after the shape of the curve and its phase is rigidly determined and such is the case in the present instance. A period 2.1721 days will harmonize the early observations with the final curve better than 2.1722. The former period is taken as final. The observations were grouped into the following 14 normal places and preliminary elements selected upon which to base a least-squares solution.

	Mean Phase from J.D. 2,422,138.0	Mean Velocity	Number of Plates	Weight	Residuals O-C	
					Prel.	Final
1.....	0.079	- 42.1	2	1	+ 9.7	+ 9.9
2.....	0.251	+ 5.4	2	1	- 7.3	- 5.6
3.....	0.377	+ 54.9	1	$\frac{1}{2}$	- 1.3	+ 1.4
4.....	0.493	+ 90.6	1	$\frac{1}{2}$	+ 2.8	+ 6.2
5.....	0.592	+ 97.4	2	1	- 8.2	- 4.5
6.....	0.779	+111.1	3	1 $\frac{1}{2}$	- 0.3	+ 3.3
7.....	0.992	+ 61.6	2	1	-12.0	- 9.7
8.....	1.082	+ 48.4	2	1	+ 2.2	+ 3.7
9.....	1.249	- 16.0	2	1	- 1.8	- 1.8
10.....	1.379	- 51.6	1	$\frac{1}{2}$	+10.9	+ 9.8
11.....	1.596	-119.0	3	1 $\frac{1}{2}$	+ 7.1	+ 4.5
12.....	1.794	-153.6	2	1	- 5.3	- 8.2
13.....	1.979	-136.5	2	1	- 5.4	- 7.5
14.....	2.078	-103.6	2 $\frac{1}{2}$	1	+ 4.6	+ 3.2

It seemed fruitless to attempt to solve for the eccentricity as the observations fitted a circular orbit very well. The element corresponding to periastron passage was taken as the instant when the velocity curve crosses the γ - axis while changing from a negative

to a positive value. In this case the formulae for the least squares solution become

$$\mu = \frac{2\pi}{P} \quad v = \mu t$$

$$V_0 = \gamma + K \sin v$$

$$dV_0 = d\gamma + \sin v dK - K\mu \cos v dT$$

PRELIMINARY ELEMENTS

Period	P = 2.1722 days
Eccentricity	e = 0.0 assumed
Velocity of system	γ = -17.3 km.
Semi-amplitude	K = 131 km.
Perihelion passage	T = J.D. 2,422,138.171

The solution requires only three unknowns γ , K, T. The different steps in the solution are recorded below.

OBSERVATION EQUATIONS

1.....	1.000x	-0.2636y	-0.9647z	- 9.7	=0
2.....	1.000	+0.2292	-0.9734	+ 7.3	
3.....	1.000	+0.5612	-0.8287	+ 1.3	
4.....	1.000	+0.8024	-0.5968	- 2.8	
5.....	1.000	+0.9383	-0.3459	+ 8.2	
6.....	1.000	+0.9824	+0.1867	+ 0.3	
7.....	1.000	+0.6939	+0.7201	+12.0	
8.....	1.000	+0.4851	+0.8744	- 2.2	
9.....	1.000	+0.0235	+1.0000	+ 1.8	
10.....	1.000	-0.3453	+0.9385	-10.9	
11.....	1.000	-0.8306	+0.5569	- 7.1	
12.....	1.000	-1.0000	+0.0178	+ 5.3	
13.....	1.000	-0.8691	-0.4945	+ 5.4	
14.....	1.000	-0.6940	-0.7200	- 4.6	

NORMAL EQUATIONS

$$\begin{aligned} 13.500x + 0.280y - 0.014z + 7.10 &= 0 \\ 6.978y + 0.513z + 22.84 &= 0 \\ 6.523z - 1.99 &= 0 \end{aligned}$$

Whence $x = -0.457$

$y = -3.296$

$z = +0.564$

where $x = d\gamma$

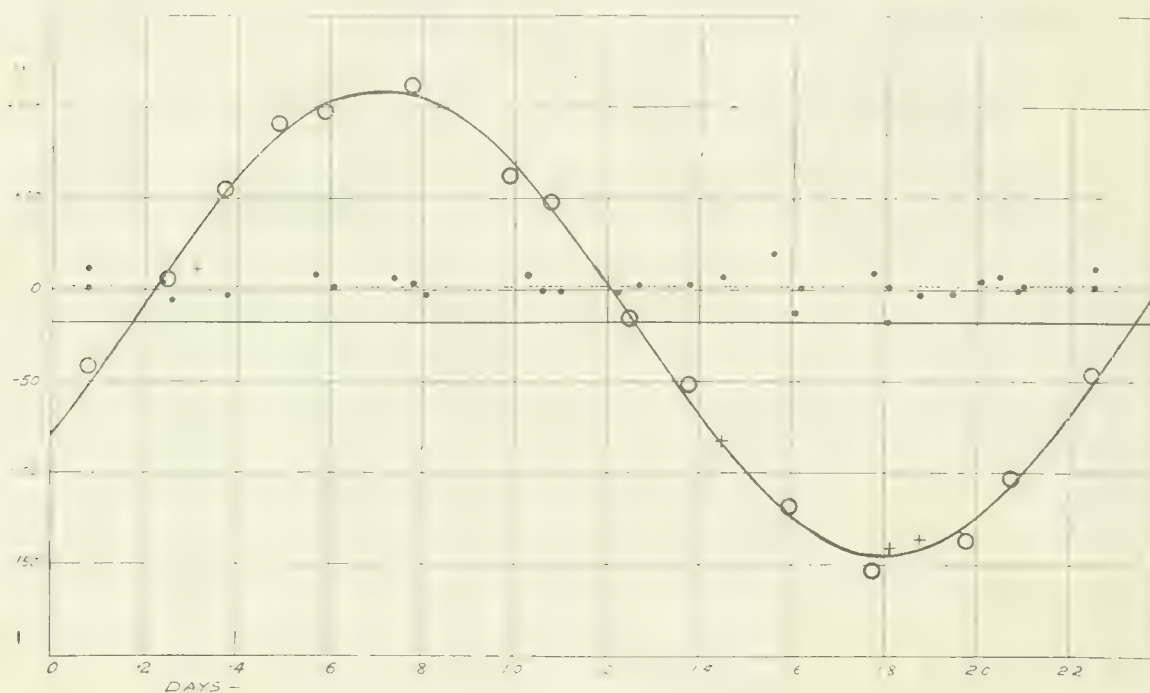
$y = dK$

$z = -K\mu dT$

When we add these corrections to the preliminary elements we have finally

Period	P = 2.1721 days
Eccentricity	e = 0.0 (assumed)
Velocity of system	γ = -17.76
Semi-amplitude	K = 127.7 km.
Perihelion passage	T = J.D. 2,422,138.172
$a \sin i$	= 3,810,000 km.
$\frac{m_1^3 \sin^3 i}{(m + m_1)^2}$	= 0.47 ☉

The results of the representation by the final elements as well as those for the preliminary will be found in the table of normal places. The Σp^2 for the preliminary elements is 585 and for the final 509. The residuals computed from the observation equations agree very closely with the final ephemeris so that there can be no doubt of the sufficiency of the solution. The residuals for the individual measures are given in the table of observations under the heading O-C. They are quoted to tenths of kilometers but are certainly not so accurately determined for they were scaled off the final graph which is shown at the end of the paper. The probable error of a single plate came out ± 7.0 km.



Radial Velocity Curve of H. R. 8427.

The result for the calcium lines is interesting. So far as the accuracy of measurement will allow they yield a constant velocity of $+1.5$ km. The velocity of the center of gravity of the system is -17.8 , while the velocity of the system toward the earth due to the sun's motion is about -14 . In most of the cases of the fixed calcium lines which have hitherto been investigated the calcium has yielded velocities which were rather closely accordant with the velocity it should have if at rest with respect to the stars in general. That is the observed velocity for the calcium seemed to be the component of the solar motion toward the star. In the present instance the observations are quite contradictory to such interpretation.

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THE ORBIT OF THE SPECTROSCOPIC BINARY H. R. 6385

BY W. E. HARPER

This star ($1900\ \alpha = 17^{\text{h}}\ 06^{\text{m}}\cdot 1^{\text{m}}$, $\delta = +12^{\circ}\ 35'$, visual magnitude 6.46, type A2) was found to be a spectroscopic binary from observations made here by Dr. R. K. Young in 1918 and 1919. The measures of his 4 plates are given in Vol. 1, No. 10 of these Publications. Twenty-eight additional plates have been secured this season, making 32 in all upon which the determination of the orbit is based. The data concerning these plates are given in the table of observations following, the successive columns being self-explanatory. For the first plate the mean of measures by Young and the writer is used. The residuals O-C are scaled from the final curve and should be accurate to 0.1 or 0.2 km. at most. The period obtained from connecting up the observations over the 3 years was 23.245 days and it was felt unnecessary to include this element in the least-squares solution. The phases, then, are reckoned from the date of periastron finally adopted using this value of the period.

OBSERVATIONS OF H. R. 6385

Plate Number	Date	Julian Date	Phase	Velocity	Lines	Residual O-C
	1918					
263	June 28.....	2,421,773.821	16.78	+25.6	16	+2.6
	1919					
1955	May 4.....	2,083.922	1.45	-32.0	11	+0.4
2276	July 6.....	146.765	17.80	+20.5	12	-2.9
2860	Aug. 29.....	200.661	1.96	-28.5	10	+1.3
	1920					
3866	Mar. 2.....	386.037	1.38	-29.9	9	+1.8
4013	April 5.....	420.937	13.03	+21.8	11	+4.9
4031	" 7.....	422.957	15.05	+17.2	16	-3.4
4052	" 9.....	424.917	17.01	+23.2	15	-0.1
4080	" 12.....	427.917	20.01	+25.2	10	+5.4
4096	" 14.....	429.004	21.10	+ 9.7	5	-2.3
4141	" 23.....	438.923	7.77	+ 2.8	15	+1.4
4165	" 25.....	440.946	9.80	+ 8.5	12	+0.3
4189	" 30.....	445.927	14.78	+16.9	13	-3.4
4209	May 2.....	447.929	16.78	+26.0	14	+3.0
4220	" 3.....	448.926	17.78	+24.0	12	+0.6
4247	" 5.....	450.930	19.78	+21.7	16	+1.2
4315	" 19.....	464.835	10.44	+ 8.9	14	-1.3
4332	" 21.....	466.862	12.47	+16.4	13	+0.7
4345	" 24.....	469.851	15.46	+19.4	14	-1.9
4357	" 30.....	475.806	21.41	+ 6.8	14	-1.8
4369	" 31.....	476.807	22.41	- 5.6	20	+1.3
4370	" 31.....	476.830	22.44	- 9.2	16	-2.2
4385	June 1.....	477.897	0.26	-22.5	15	+3.1
4444	" 20.....	496.810	19.17	+23.3	9	+1.1
4462	" 25.....	501.819	0.93	-34.8	17	-3.7
4477	" 27.....	503.794	2.91	-24.0	17	+0.3
4482	" 28.....	504.815	3.93	-19.8	17	-2.4
4500	" 29.....	505.800	4.92	-12.2	16	-0.5
4509	" 30.....	506.770	5.88	- 4.8	16	+2.0
4525	July 1.....	507.809	6.92	- 2.2	22	-0.2
4533	" 2.....	508.721	7.84	+ 2.3	16	+0.8
4633	" 16.....	2,422,522.729	21.84	+ 3.2	11	+0.4

NORMAL PLACES

	Mean Phase		Velocity	Weight	Residuals O-C	
	Prel.	Final			Prel.	Final
1.....	15.89	16.02	+22.0	5.0	-0.9	-0.3
2.....	17.36	17.49	+22.6	3.5	-0.9	-0.9
3.....	19.56	19.69	+23.1	3.5	+3.6	+2.0
4.....	21.21	21.34	+ 7.5	2.0	+0.2	-2.2
5.....	21.72	21.84	+ 3.2	1.0	+2.5	+0.4
6.....	22.30	22.43	- 7.2	3.5	+1.2	-0.1
7.....	.13	0.26	-22.5	1.5	+2.6	+3.1
8.....	.81	0.94	-34.8	1.5	-4.2	-3.7
9.....	1.29	1.42	-31.0	2.0	+0.5	+0.6
10.....	2.43	2.56	-25.7	2.5	+1.1	+0.9
11.....	4.29	4.42	-16.0	3.0	-1.7	-1.5
12.....	6.33	6.46	- 3.4	3.5	-0.4	+0.5
13.....	7.67	7.80	+ 2.6	3.0	-0.4	+0.9
14.....	9.99	10.12	+ 8.7	2.5	-2.3	-0.8
15.....	13.33	13.46	+18.4	3.5	-0.8	+0.5

The observations were combined as in the preceding table and preliminary elements were obtained in the usual graphical way. The maximum of the curve is smooth and rounded and more observations than were really necessary there were secured before the true form of the curve was recognized. In general the weight assigned to a group is based upon the total number of lines measured on the plates comprising the group.

PRELIMINARY ELEMENTS

Period	$P = 23.245$ days
Eccentricity	$e = .40$
Longitude of periastron	$\omega = 135^\circ$
Velocity of system	$\gamma = + 3.78$ km.
Semi-amplitude of range	$K = 27.5$ km.
Periastron passage	$T = \text{J.D. } 2,421,780.416$

Making the following transformations for homogeneity the observation equations were built up according to the formula of Lehmann-Filhés.

$$\begin{aligned}
 x &= \delta\gamma \\
 y &= \delta K \\
 z &= K. \delta e \\
 u &= K. \delta \omega \\
 v &= [0.98476] \delta T
 \end{aligned}$$

OBSERVATION EQUATIONS FOR H. R. 6385

1	1.000x	+ .695y	- .930z	- .077u	- .091v	+ .9=0
2	1.000	+ .716	- .644	- .325	+ .022	+ .9
3	1.000	+ .571	+ .438	- .803	+ .425	-3.6
4	1.000	+ .129	+1.467	-1.194	+1.189	- .2
5	1.000	- .111	+1.433	-1.268	+1.490	-2.5
6	1.000	- .443	+ .890	-1.270	+1.732	-1.2
7	1.000	-1.050	- .870	- .924	+1.254	-2.6
8	1.000	-1.253	-1.056	- .527	+ .439	+4.2
9	1.000	-1.282	- .617	- .238	- .073	- .5
10	1.000	-1.111	+ .653	+ .278	- .649	-1.1
11	1.000	- .658	+1.167	+ .644	- .660	+1.7
12	1.000	- .245	+ .672	+ .716	- .498	+ .4
13	1.000	- .029	+ .255	+ .684	- .415	+ .4
14	1.000	+ .263	- .376	+ .555	- .311	+2.3
15	1.000	+ .560	- .930	+ .254	- .200	+ .8

From these were obtained the normal equations

$$\begin{array}{rcllclcl}
 4.150x & - & .251y & + & .204z & - & .562u & + & .537v & + & .285=0 \\
 & & 1.922 & - & .700 & + & .029 & - & .156 & + & .013 \\
 & & & & 2.936 & - & .352 & + & .588 & - & 2.158 \\
 & & & & & & 2.018 & - & 2.008 & + & 2.649 \\
 & & & & & & & & 2.299 & - & 2.434
 \end{array}$$

resulting in corrections as follows

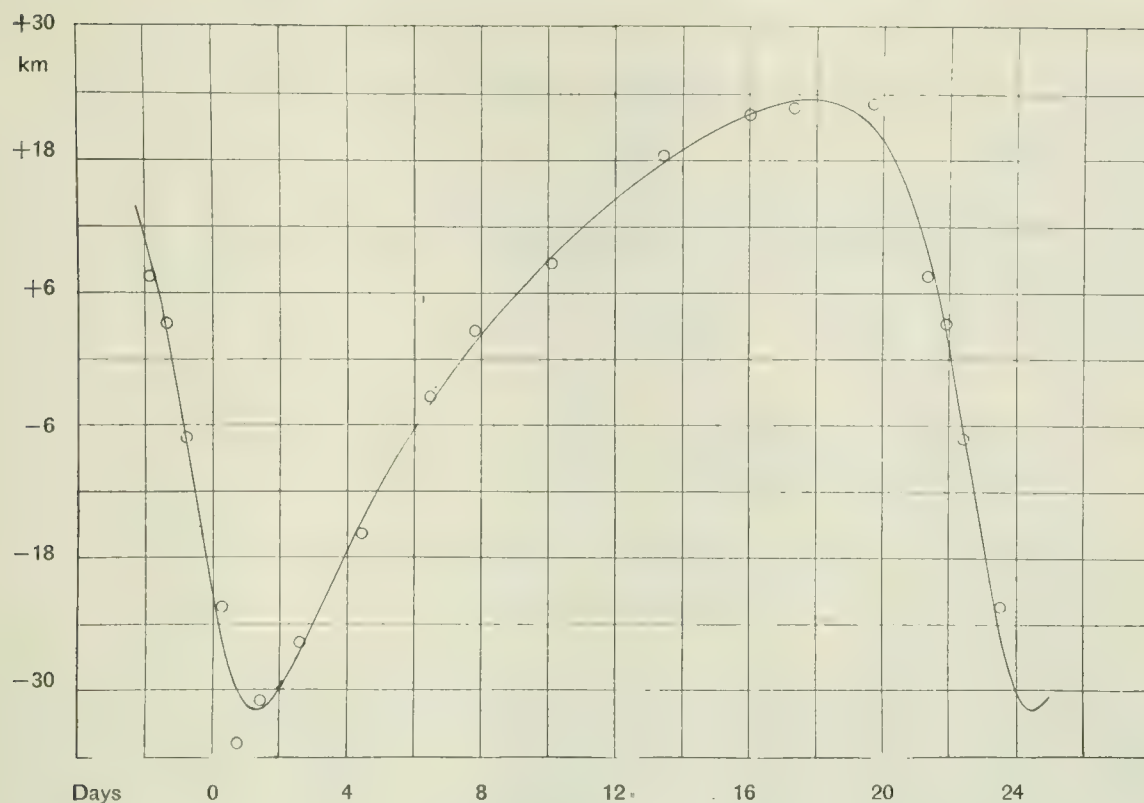
$$\begin{aligned}
 \delta\gamma &= - .27 \text{ km.} \\
 \delta K &= + .17 \text{ km.} \\
 \delta e &= + .027 \\
 \delta\omega &= -5^\circ.15 \\
 \delta T &= - .126 \text{ days.}
 \end{aligned}$$

The final values, then, with their probable errors are the following

FINAL ELEMENTS

$$\begin{aligned}
 P &= 23.245 \text{ days} \\
 e &= .427 \pm .014 \\
 \omega &= 129^\circ.85 \pm 2^\circ.46 \\
 \gamma &= +3.51 \text{ km.} \pm 0.30 \text{ km.} \\
 K &= 27.67 \text{ km.} \pm 0.45 \text{ km.} \\
 T &= \text{J.D. } 2,421,780.290 \pm 0.116 \text{ days} \\
 a \sin i &= 7,997,400 \text{ km.}
 \end{aligned}$$

$$\frac{m_1^3 \sin^3 i}{(m + m_1)^2} = 0.038 \odot$$



Radial Velocity Curve of H.R. 6385.

The solution improved the agreement considerably, the sum of the squares of the residuals for the normal places being reduced from 128.7 to 76.7. One solution was found to be sufficient. The probable error of a plate as determined from the last two columns of the table of observations is ± 1.50 km. per sec. and is satisfactory for this type of spectrum measured on the micrometer engine.

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THE ORBIT OF THE SPECTROSCOPIC BINARY BOSS 5900

BY W. E. HARPER

This star (1900 $\alpha = 22^h 48.2^m$, $\delta = +16^\circ 19'$, visual magnitude 5.72, type Ko) was found to be a spectroscopic binary by the writer from the second plate made in the autumn of 1919. Ten plates were secured at that time and seven more have been added this summer making seventeen observations upon which the determination of the orbit rests. They are all measured on the Hartmann comparator, a spectrum of the star α Boötis (No. 2702) serving as the standard. The data of the places follow.

OBSERVATIONS OF BOSS 5900

Plate Number	Date	Julian Date	Phase	Velocity	Residual O-C
1919					
2915	Sept. 9	2,422,211.845	5.50	+20.6	+0.6
2972	" 15	217.786	11.44	-7.2	-1.8
3109	Oct. 3	235.762	4.77	+19.5	+1.2
3172	" 13	245.766	14.77	-34.0	-1.8
3203	" 18	250.716	19.72	-47.2	-2.9
3220	" 24	256.713	1.07	-7.4	-3.6
3306	Dec. 1	294.617	14.32	-27.6	+1.4
3381	" 5	298.566	18.27	-42.4	+3.6
3392	" 7	300.561	20.27	-43.3	-0.7
3406	" 8	301.546	21.25	-36.8	+1.3
1920					
4322	May 19	464.973	12.13	-12.0	-0.8
4377	" 31	476.966	24.12	-18.9	-1.7
4472	June 25	501.960	24.47	-14.0	+0.3
4494	" 28	504.971	2.83	+9.2	+0.1
4545	July 2	508.957	6.82	+21.4	+1.5
4578	" 5	511.953	9.81	+7.1	+0.1
4649	" 18	2,422,524.933	22.79	-25.5	+2.4

The period deduced from connecting up the observations of the two seasons was 24.65 days and this element was not considered in the least-squares solution. A plot according to this value showed the observations to follow a sine curve so closely that it was decided to consider the orbit circular and solve only for the velocity of the system, the semi-amplitude and an initial epoch, here taken as the time when the light-giving star is closest to the sun or when the orbital velocity is passing from negative through zero to positive values. In this case the formulae are much simplified. Where v is the angle reckoned from this position we have

$$V = \gamma + K \sin v \dots \dots \dots (1)$$

$$\text{and since } v = \mu (t - T) \dots \dots \dots (2)$$

$$\text{then } \delta V = \delta \gamma + \sin v \cdot \delta K - K \cdot \mu \cdot \cos v \delta T \dots \dots \dots (3)$$

PRELIMINARY ELEMENTS

$$P = 24.65 \text{ days}$$

$$e = 0.$$

$$\gamma = -12.9 \text{ km.}$$

$$K = 33.5 \text{ km.}$$

$$T = \text{J.D. } 2,422,240.936$$

Making the transformations for the sake of homogeneity

$$x = \delta \gamma$$

$$y = \delta K$$

$$z = -K \cdot \mu \cdot \delta T$$

we obtain 17 equations of form (3) as follows, equal weight being assigned to each.

OBSERVATION EQUATIONS FOR BOSS 5900

1	1.000x	+ .988y	- .153z	-0.4=0
2	1.000	+ .208	+ .978	+1.3
3	1.000	+ .943	- .334	-0.8
4	1.000	- .596	+ .803	+1.1
5	1.000	- .946	- .324	+2.6
6	1.000	+ .284	- .959	+4.0
7	1.000	- .500	+ .866	-2.1
8	1.000	- .999	+ .040	-4.0
9	1.000	- .893	- .451	+0.5
10	1.000	- .752	- .659	-1.3
11	1.000	+ .035	+ .994	+0.3
12	1.000	- .120	- .993	+2.0
13	1.000	- .031	- .999	+0.1
14	1.000	+ .670	- .742	+0.3
15	1.000	+ .984	+ .179	-1.3
16	1.000	+ .586	+ .810	-0.4
17	1.000	- .443	- .896	-2.2

From these were obtained the normal equations:

$$\begin{array}{rcccc}
 17.000x & - & .582y & - & 1.841z & - & .300 = 0 \\
 & & 7.819 & + & .454 & + & 2.154 \\
 & & & & 9.165 & - & 4.140
 \end{array}$$

resulting in small corrections as follows:

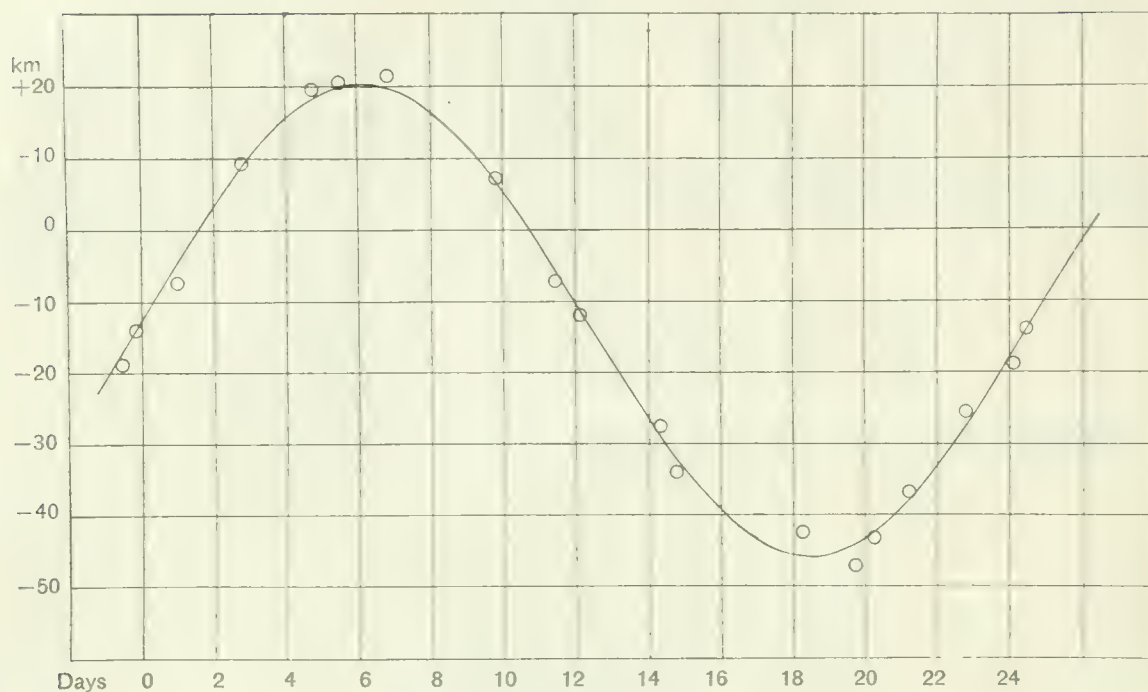
$$\begin{aligned}
 \delta\gamma &= +.06 \text{ km.} \\
 \delta K &= -.30 \text{ km.} \\
 \delta T &= +.056 \text{ days.}
 \end{aligned}$$

The final values, then, with their probable errors are the following.

FINAL ELEMENTS

$$\begin{aligned}
 P &= 24.65 \text{ days} \\
 e &= 0 \\
 \gamma &= -12.84 \text{ km.} \pm 0.34 \text{ km.} \\
 K &= 33.20 \text{ km.} \pm 0.49 \text{ km.} \\
 T &= \text{J.D. } 2,422,240.992 \pm 0.054 \text{ days} \\
 a \sin i &= 11,254,000 \text{ km.} \\
 \frac{m^3 \sin^3 i}{(m + m_1)^2} &= .094 \odot
 \end{aligned}$$

The solution reduced the sum of the squares of the residuals very slightly,—from 59.7 to 58.4—but as the differences between equation and ephemeris residuals are less than 0.1 km no second solution need be considered, and the preliminary elements adopted were, therefore, very close to the truth. The probable error of a plate is ± 1.26 km per second.



Radial Velocity Curve of Boss 5900 Showing Individual Observations.

The graph shows the individual observations plotted on a sine curve. It has been noted by others and attention may again be directed to the low values of the eccentricity found in several stars of G- and K-types, and exemplified in the case before us. It would seem that the early idea of the eccentricity being a function of the type should be modified, as its variation with the period within the type is as marked as the variation from type to type.

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THE SPECTROSCOPIC ORBIT OF TX HERCULIS

BY J. S. PLASKETT

The eclipsing variable TX Herculis α 17^h 15.4^m, δ + 42° 0', spectral type A2 magnitude 8.0, has had a photometric orbit determined by Shapley* and although this orbit is classified by him as of the third grade only, the spectroscopic work is in agreement with the photometric and there seems no question that both are substantially correct.

TX Herculis was placed under observation on March 17, 1920 and sixteen plates were intermittently obtained between that date and August 13. All were measured but two of them, one near primary and one near secondary minimum, were not, for obvious reasons, used in determining the orbit. The spectra, for both components are visible, are of type A2 with numerous sharp lines and are easily measurable. The lines of the principal component are, however, considerably stronger and better defined than those of the secondary and the measures are consequently more reliable. The star, however, is faint, 8.0 visual magnitude at maximum, and some of the plates are rather weak. If the seeing is good one hour's exposure gives a good spectrum of linear dispersion 29A per mm. at H γ , but this has to be considerably increased if the seeing is poor.

The following table contains observational and other data of TX Herculis. The first three columns contain the plate number, the date and the Julian date of the observations. The fourth column contains the phase computed from the initial phase J. D. 2,418,967.3925 + 2.059786 days given by Shapley. The fifth and sixth columns contain the measured velocities of principal and secondary components, these measures having been repeated and the mean used in the case of some of the plates. The seventh and eighth columns contain the residuals in the sense observed minus computed from the corrected orbit.

*Contributions from Princeton Observatory, 3, p. 88.

OBSERVATIONS OF TX HERCULIS

Plate Number	Date	Julian Date	Phase	Velocity		Residuals O-C	
				Principal	Secondary	Principal	Secondary
	1920						
3942	Mar. 17	2,422,401.047	2.051		- 16.6		
4123	April 22	2,437.882	1.810	+ 86.6	-104.6	-0.94	+10.56
4171	" 25	2,440.981	0.790	-101.4	+100.7	-3.45	+ 1.02
4234	May 4	2,449.885	1.455	+ 97.8	-133.1	-7.25	+ 2.34
4291	" 13	2,458.872	0.143	- 42.2	+ 55.2	+1.02	+18.89
4431	June 18	2,494.867	1.121	+ 5.0			
4481	" 28	2,504.783	0.739	-115.7	+120.1	-6.59	+ 7.50
4524	July 1	2,507.777	1.673	+106.1	-132.1	-4.32	+ 9.56
4558	" 4	2,510.756	0.532	-124.9	+135.7	+2.18	+ 2.28
4568	" 5	2,511.773	1.549	+111.3	-142.4	-2.54	+ 3.23
4607	" 8	2,514.759	0.416	-118.9	+124.4	-2.45	+ 3.29
4621	" 14	2,520.764	0.241	- 76.3	+ 67.8	-0.73	- 5.95
4722	" 27	2,533.757	0.873	- 71.7	+ 92.8	+3.51	+19.46
4734	" 28	2,534.780	1.898	+ 64.8	+106.4	+0.86	-18.57
4868	Aug. 12	2,549.722	0.362	-111.5	+109.1	-4.78	- 0.74
4880	" 13	2,550.727	1.367	+ 88.3	-126.7	-0.24	-10.38

When the observations were plotted on cross section paper it was at once seen that they would be satisfied by a circular orbit and that there is no likelihood of any eccentricity as some of the photometric work seemed to indicate, but that there was a displacement of phase, the spectroscopic occurring later than the photometric. It was also evident that the observations of the principal component gave a much smoother curve and were apparently more accurate than those of the secondary and that further better agreement would be obtained if it were possible to assign a different velocity of the system to the two components, the observations being best satisfied with about -8 km. for principal and -3 km. for secondary components. However, as such a condition is impossible there must have been some condition in the character of the secondary spectrum, whose lines were considerably fewer, weaker, and poorer defined than those of the primary, which caused this apparent displacement.

Preliminary elements were selected graphically from the plotted observations consisting of the following

Semi-amplitude of principal component	$K_1 = 119$ km.
Semi-amplitude of secondary component	$K_2 = 139$ km.
Velocity of system	$\gamma = -5$ km.
Time of principal phase	$T = 0.03$ days (later than photometric)

Using these elements, an ephemeris was computed and observation equations were constructed from the differential expression for a circular orbit obtained from the

equation $r = \gamma + K \sin \theta$,

$$\delta r = \delta \gamma + \sin \theta_1 \delta K_1 + \sin \theta_2 \delta K_2 + (K_1 \cos \theta_1 + K_2 \cos \theta_2) \delta \theta.$$

Each of the observations except the first and sixth which occurred near the minima where the spectra were blended was used as a normal place but the three plates 4291, 4722, 4734, which occurred nearest the minima and in which the separation of the component lines was least, were given only half weight.

The coefficient of $\delta \theta$ in each observation equation was divided by 100 in order to make the magnitudes of all the coefficients more nearly equal. Forming the normal equations in the usual way from these observation equations there resulted the following

$$\begin{array}{rcl} 25.0 \delta \gamma - .5702 \delta K_1 + .5702 \delta K_2 + .1338 \delta \phi & = & -35.47 \\ +8.3310 \delta K_1 & + & .3230 \delta \phi = +16.39 \\ & +8.3310 \delta K_2 & + .4467 \delta \phi = +7.32 \\ & & +11.4406 \delta \phi = -39.19 \end{array}$$

where as before stated $\delta \phi = 100 \delta \theta$

The solution of these normals resulted in the following corrections and final elements of TX Herculis

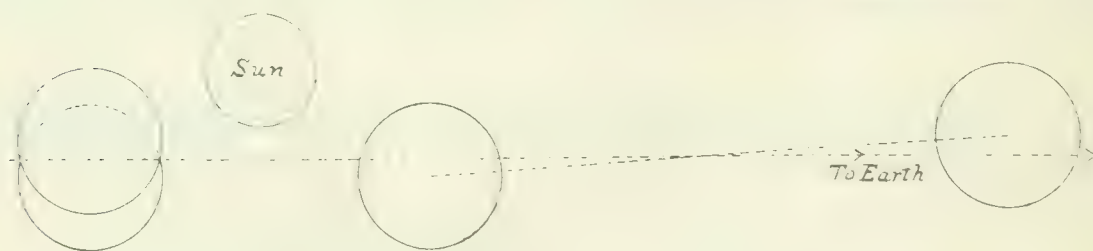
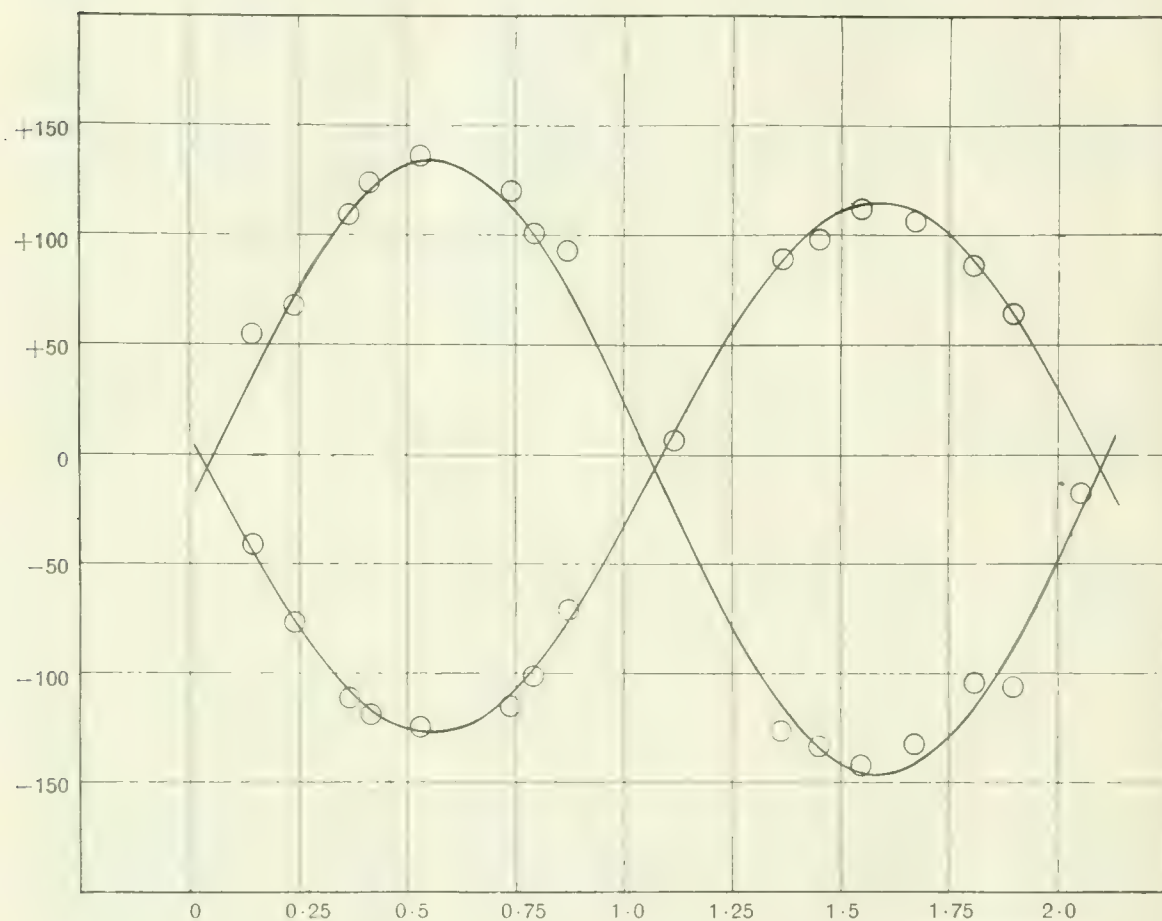
$$\begin{array}{ll} \delta \gamma & = -1.38 & \gamma & = -6.38 \pm 1.0 \\ \delta K_1 & = +2.01 & K_1 & = 121.01 \pm 1.0 \\ \delta K_2 & = +1.16 & K_2 & = 140.16 \pm 2.4 \\ \delta \phi & = - .0351 & & \\ & = -2^\circ.01 & T & = .0415 \pm .0049 \text{ days (later than} \\ \delta T & = + .0115 \text{ days} & & \text{photometric phase)} \end{array}$$

The sine curves resulting from these elements are shown in the accompanying figure with the observations plotted as circles. The sum of the squares was reduced about 15 per cent by this solution and the resulting orbit is as satisfactory as can be expected from the observations. From the computed residuals given in the table of observations, the probable error of a single plate for the principal star is ± 2.6 and for the secondary ± 7.2 km. per second.

Assuming Shapley's darkened orbit as the most probable which gives the radii of the two stars as 0.125 their separation and the inclination as $86^\circ 16'$ we obtain from the spectroscopic orbit by the well known formulae, the following dimensions of the system of TX Herculis.

Separation of two stars	a	$= 7,413,000 \text{ km.} = 10.66 \odot$
Radius of each star	γ	$= 927,000 \text{ km.} = 1.33 \odot$
Total mass of system	m	$= 3.81 \odot$
Mass principal star	m_1	$= 2.04 \odot$
Mass secondary star	m_2	$= 1.77 \odot$
Density principal star	ρ_1	$= 0.87 \odot$
Density secondary star	ρ_2	$= 0.75 \odot$

Using Shapley's assumption of -1.8 magnitudes as the surface intensity of an A2 star we have the absolute magnitude of the principal component of TX Herculis as 2.44 while its apparent magnitude is 8.73 . The well known formula for parallax gives this quantity then as 0.0055 .



Velocity Curve and Relative Dimensions of TX Herculis

The orbit is simple and with no difficulties except the apparent difference in systematic velocity of the two components of about 5 km. per second which when the character of the lines of the second component is considered is probably explained by some slight asymmetry of distribution of intensity sufficient to shift their measured

position by this small amount, about 2.5 microns on the plates. The displacement of phase, the spectroscopic being about an hour later, in the same direction as found in RS Vulpeculae and TW Draconis but in the opposite direction to the discrepancies found by Schlesinger, must likely be due to a slight error in the photometric period which if of the order of one one-hundred-thousandth of a day or, say, one second would be sufficient to account for the discrepancy when brought forward from the initial phase. The spectroscopic observations are of sufficient accuracy to determine the phase with a probable error of about 7 minutes which, with a deviation of an hour leaves the discrepancy more likely to be accounted for by an error in the photometric observations which at the best are somewhat uncertain. The relative dimensions and positions of the two bodies as compared with the sun are given in the accompanying figure.

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THE SPECTROSCOPIC ORBIT OF Y CYGNI

BY J. S. PLASKETT

The eclipsing variable Y Cygni α 20 48.1, $\delta + 34^{\circ} 17'$, spectral type B2, magnitude 7.0, has been very widely observed for light variations since its discovery but the observations are in an exceedingly unsatisfactory state and a long photometric series is required to obtain a satisfactory orbit. This difficulty is mainly due to the period which is only about five minutes less than three days. Consequently only a small part of the cycle can be observed in one season and several years would be required to entirely cover the period.

Dunér in 1900 determined an elaborate orbit* for this star which had an eccentricity of 0.145, very high for such a close pair, with a secular change in the elements. Later observations disagreed with these elements and in 1914 Shapley determined another photometric orbit† from Wendell's incomplete observations using Dunér's period. This latter orbit has been used in this work and so far as the spectroscopic results can determine, Shapley's orbit agrees with them much more closely than Dunér's.

In pursuance of a programme of obtaining spectroscopic orbits for all eclipsing variables brighter than the eighth magnitude, and within reach at this latitude, this star was placed under observation at Victoria on August 6, 1919 and between that date and August 9, 1920, twenty-four spectra were obtained, all of which have been measured. Nineteen of these plates were used in determining the orbit, the remaining five being too close to the minima, with consequent blending of the lines of the components, to be safely used.

The spectra, for both components of nearly equal intensity are visible, are exceedingly difficult to measure as the lines are not only very broad and diffuse but are also very faint and lacking in contrast and in many cases are barely visible under the microscope. This lack of contrast is probably partly due to the superposition on the absorption line of the one star of the continuous spectrum of the equally bright companion thereby reducing the contrast, which at best, as the plates taken at minimum, when most of the light is from one star only, show, is never very great. The spectral type given as A is in reality, so far as can be judged from the very diffuse and faint lines, B2. Sharp single calcium H and K lines are present, as is so often the case with diffuse lined B types and these lines are practically stationary, do not share in the large oscillations of the hydrogen and

*Ap. J. 11, p. 175. †Contributions from Princeton Observatory, No. 3, p. 88.

helium lines and give a widely different value for the velocity of the system. The character of the hydrogen and helium lines and the uncertainty of measurement may be judged from the probable errors of a single plate which amount to ± 17.2 km. for the principal and ± 16.0 km. per second for the secondary component. Nevertheless, owing to the great range, the separation of the lines being nearly 500 km. at maximum, the relative error in the dimensions of the system can not be excessively great. The lines measured have included the hydrogen series $H\beta$, $H\gamma$, $H\delta$; helium 4472, 4388, 4144, 4026; carbon 4267 and calcium H and K. None of the other helium lines or of the lines of other elements usually present in stars of this type are visible.

The following table contains the observations of Y Cygni in chronological order. The first three columns give the plate number, the date and Julian date of the observation. The fourth column contains the phase computed from the initial phase used by Shapley J.D. 2,420,036.392 + 2.996332 days while the fifth and sixth columns contain the measured velocities from the doubled lines, in general the mean of two or three separate measures. The seventh column gives the velocity from the calcium lines, generally from the K line only but on two plates from the mean of the H and K lines. The eighth and ninth columns contain the residuals of the individual plates in the sense observed minus computed as obtained from the final elements. It will be noticed that these residuals are not given for those plates occurring near primary or secondary minimum, at phases near 0 or 3.0 and 1.5 days, as these plates were not used in obtaining the orbit.

OBSERVATIONS OF Y CYGNI

Plate Number	Date	Julian Date	Phase	Velocities		Calcium	Residuals O-C	
				Prin.	Sec.		Prin.	Sec.
1919								
2600	Aug. 6	2,422,177.846	2.073	+182.3	-235.5		+21.3	+41.1
2981	Sept. 16	2,218.682	0.961	-246.6	+151.8		+11.1	-14.9
3067	" 23	2,225.760	2.046	+138.5	-287.6		-16.7	-17.3
3160	Oct. 8	2,240.731	2.035	+133.0	-261.0		-2.0	+7.0
3280	Nov. 25	2,288.570	1.933	+110.4	-226.3		-17.5	+14.5
3298	" 29	2,292.574	2.941		97.7			
3355	Dec. 4	2,297.553	1.927	+106.3	-216.4	-4.5	-19.9	+22.5
3411	" 11	2,304.578	2.959		94.8			
1920								
3444	Jan. 1	2,325.584	2.991		-75.0			
3449	" 3	2,327.558	1.969	+105.4	-248.8	-9.7	-32.5	+2.7
4293	May 13	2,458.878	1.451	-61.2		-12.3		
4448	June 20	2,460.922	0.542	-250.4	+129.6	-6.7	+1.9	-41.3
4531	July 1	2,507.926	2.557	+122.5	-277.7		-6.5	-35.7
4541	" 2	2,508.838	0.473	-247.4	+128.0	-13.1	-10.9	-25.9
4601	" 7	2,513.910	2.548	+156.5	-254.8	-7.5	+25.4	-10.1
4661	" 22	2,528.745	2.401	+202.3	-325.8	-13.1	+39.0	-46.7
4693	" 25	2,531.766	2.425	+210.3	-292.1	-15.2	+51.1	-17.4
4726	" 27	2,533.853	1.516	-67.8		-11.1		
4748	Aug. 1	2,538.708	0.380	-200.0	+142.6		+9.2	+18.3
4761	" 1	2,538.977	0.649	-239.9	+179.2		+28.2	-8.9
4780	" 4	2,541.772	0.446	-207.6	+144.2	-12.6	+22.3	-2.5
4787	" 4	2,541.983	0.657	-272.0	+194.4		-3.2	+5.5
4807	" 7	2,544.871	0.549	-241.2	+181.3		+12.8	+8.5
4829	" 9	2,546.795	2.473	+189.0	-294.1	-12.4	+38.8	-29.2

These observations were collected into the following table of 10 normal places in which in the successive columns are given the number, the number of plates and corresponding weight, the mean phase in days and in the orbital angle of the primary from minimum, the mean velocities of primary and secondary and the residuals of primary and secondary from the preliminary and corrected orbits. The maximum difference of phase occurs in No. 1 where it is 0.093 days.

NORMAL PLACES OF γ CYGNI

Number	Number of Plates	Mean Phases		Mean Velocities		Residuals (Prel.)		Residuals (Final)	
		Days	Primary Angle	Primary	Secondary	Primary	Secondary	Primary	Secondary
1.....	3	0.434	232.14	-218.3	+138.3	+13.28	- 1.18	+ 7.59	- 4.08
2.....	2	0.546	245.60	-245.8	+155.4	+13.66	-13.17	+ 7.22	-16.37
3.....	2	0.653	258.46	-255.9	+186.8	+19.45	+ 1.65	+12.60	- 1.73
4.....	1	0.961	295.46	-246.6	+151.8	+11.07	-14.90	+ 4.68	-18.08
5.....	2	1.483	358.18	- 64.5		- 6.45			
6.....	3	1.943	53.45	+107.4	-230.5	-27.36	+12.29	-23.36	+13.44
7.....	3	2.051	66.42	+151.3	-261.4	- 9.49	+ 8.56	- 4.80	+10.00
8.....	3	2.433	112.32	+200.5	-304.0	+37.73	-31.98	+42.47	-30.52
9.....	2	2.547	126.01	+139.5	-266.2	+ 3.45	-22.06	+ 7.49	-20.90
10.....	3	2.964	176.12		- 89.2		-22.95		

These normal places plotted on cross section paper as shown in the accompanying velocity curve indicated to the order of accuracy of the observations that the orbit was circular and that the spectroscopic and photometric phases agreed. Preliminary elements were assumed as follows giving the residuals in the seventh and eighth columns above.

$$\text{Semi-amplitude primary} = K_1 = 230 \text{ km. per sec.}$$

$$\text{Semi-amplitude secondary} = K_2 = 240 \text{ km. per sec.}$$

$$\text{Velocity of system} = \gamma = -50 \text{ km. per sec.}$$

From the differential equations $\delta\gamma + \delta K_1 \sin \theta_1 = \delta v_1$ and $\delta\gamma + \delta K_2 \sin \theta_2 = \delta v_2$ simple observation equations resulting in the following normal equations were obtained

$$38.000 \delta\gamma + 3.048 \delta K_1 - 3.048 \delta K_2 = + 7.68$$

$$14.596 \delta K_1 = -86.17$$

$$14.596 \delta K_2 = +34.28$$

The solution of these equations resulted in the following corrections and final values of the elements.

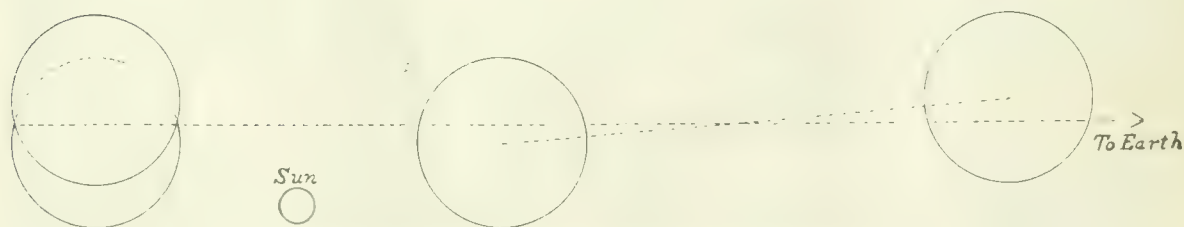
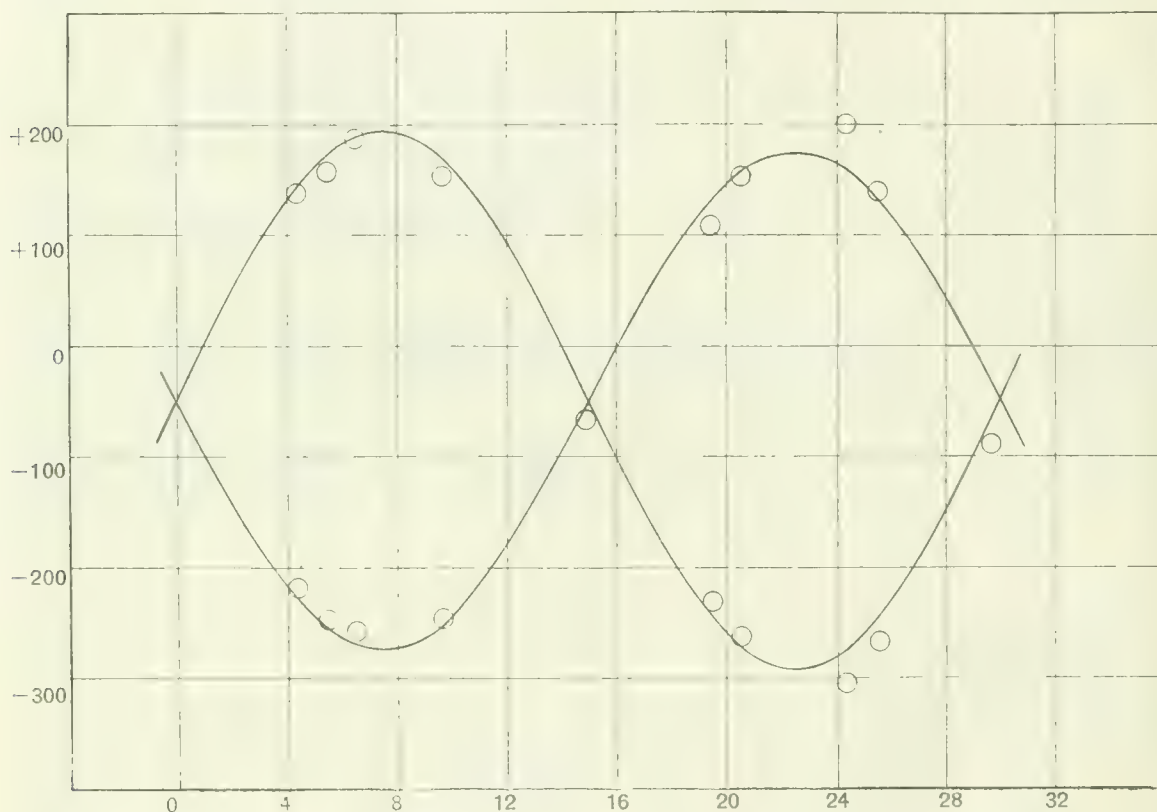
$$\delta\gamma = +0.89 \quad \gamma = -49.1 \pm 2.3$$

$$\delta K_1 = -6.09 \quad K_1 = +223.9 \pm 4.1$$

$$\delta K_2 = +2.54 \quad K_2 = +242.5 \pm 4.0$$

The probable error of a normal place of unit weight is ± 13.2 and of a single plate ± 17.2 for the primary and ± 16.0 for the secondary components. The orbit, although probably as good as can be obtained from spectra with such diffuse lines can not be considered as

entirely satisfactory and final principally on account of the high residuals of normal place No. 8 where the separation of the lines of the components is about 70 kms. per second higher than required by the orbit. These plates were remeasured and although the lines are very diffuse, they are at least as good as at other phases and I believe the increased separation is a real phenomenon and that further observations should be obtained in



Velocity Curve and Relative Dimensions of Y Cygni

future seasons to fill up the gaps in the cycle and enable the cause of this discrepancy to be determined. It might be attributed to eccentricity such as Dunér found but it is strange that all other parts of the curve should follow a circular orbit quite as closely as the character of the spectra and the accuracy of the measures warrant and the only solution seems to be further observations of this interesting and possibly complex system.

Another interesting feature is the behaviour of the narrow sharp calcium H and K lines which have been measured in all spectra which were strong enough to show them distinctly. There can be no reasonable doubt that these lines are practically stationary as on this assumption the mean velocity comes out as -10.7 ± 0.7 with a probable error per plate (usually only the K line) of ± 2.2 kms. per second. The difference between the velocity of the system as determined from the sharp calcium and the diffuse hydrogen and helium lines is nearly 40 km. per second, much larger than the difference usually found in similar stars. Dr. Young has recently collected the data concerning the sharp stationary calcium lines in B-type binary or single stars and concludes that the calcium vapour is connected with and moving with the star. He finds in general the difference in velocity is negligible when the character of the diffuse lines is considered and explains the discrepancy, where present, by considering that the same cause which makes the lines broad and diffuse may easily shift their centre of intensity the required small amount. Although it is difficult to see how so great a discrepancy as 40 km. can be accounted for in this way there is no denying the fact that a systematic velocity of -49 km., for such a massive B star as this, is very much higher than can reasonably be expected.

There remains to combine the spectroscopic and photometric data to obtain the absolute dimensions of the system. According to the probable errors of the spectroscopic orbit leaving aside the abnormal features discussed above, the dimensions should be correct to about two per cent and even taking all uncertainties into consideration it is evident that we are dealing with the minimum probable dimensions. Accepting the data from Shapley's darkened orbit and using the well known formulae for determining $a \sin i$ and $(m_1 + m_2) \sin^3 i$ we obtain

Radius principal star	r_1	=	3,216,000 km.	=	4.6 \odot
Radius secondary star	r_2	=	3,216,000 km.	=	4.6 \odot
Separation of two stars	a	=	19,294,000 km.	=	27.7 \odot
Mass principal star	m_1			=	16.6 \odot
Mass secondary star	m_2			=	15.3 \odot
Total mass system	m			=	31.9 \odot
Density principal star	ρ_1			=	0.170 \odot
Density secondary star	ρ_2			=	0.158 \odot

If we assume with Shapley* that the intensity of a B2 star as compared with the sun is -2.8 magnitudes the absolute magnitude of the principal component is -1.25 and when its apparent magnitude is 7.7 its parallax will be $0''.0016$. The velocity curve and the relative dimensions and appearance of this system, one of the two or three most massive known, at primary eclipse and maximum separation are given in the accompanying figure. This orbit should not be considered final as it is proposed to obtain observations in future seasons and to combine all observations with further photometric work which it is understood is being carried on, in the hope of obtaining more complete information about this very interesting system.

* Astrophysical Journal 40, p. 415.



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THE CALCIUM LINES H AND K IN EARLY TYPE STARS

BY REYNOLD K. YOUNG

In 1904 Hartmann¹ discovered that the calcium lines H and K in the spectrum of δ Orionis did not share in the large oscillation shown by the other lines. While the hydrogen, helium and other elements gave a displacement, which interpreted as the result of radial velocity, amounted to about two hundred kilometers per second, the calcium lines remained stationary within the error of measurement. Many other stars have been found which show the same effect and what was once thought to be an exceptional phenomenon is now quite usual. Miss Heger² has recently added the important discovery that several stars which show the stationary calcium lines also give constant velocities for the sodium lines D₁ and D₂.

At the present time there is a considerable amount of material bearing on the subject scattered through the periodicals, more in fact than some writers seem to realize. It is the object of the present paper to collect this and to add such unpublished data as the writer has at his disposal. Some of the suggestions which have been made from time to time as to the nature and cause of the calcium absorption will be discussed in the light of present information and an attempt made to decide on the most favourable hypothesis. It is hoped also that the collection of material already at hand will show best where we can direct our energies in securing further observations.

Observational Material

The Harvard Revised Photometry, Volume 50, lists 937 stars as belonging to B-type. Of these only 303 are in the northern hemisphere. As will be seen presently the phenomenon is connected only with stars of early B-type. There are only 64 stars listed in the northern skies earlier than B3 and we have already at hand material for the majority of these.

Table I contains a list of stars which have either been published as showing peculiar calcium lines or are known from other sources to belong to the class. It includes the twenty-four stars given in the Publications of the Lick Observatory, Volume 13 and many others discovered later. The list is not exhaustive, due to material doubtless at hand at other observatories but not yet published. In the *Astrophysical Journal*,

Rufus⁵ publishes a list of five Oe5 stars which he mentions as showing small range. These have not been included in the table. In 1909 Frost⁴ found that he was able to list twenty-five stars showing sharp and narrow H and K lines and for some of these we believe no information has been published. However, the table gives all those stars which have been studied with any detail and includes many stars which have not been considered by various writers in commenting on the peculiar behaviour of the calcium lines^{5,6}. Orbits have been published for a bare majority of the stars, a few of them have been extensively observed without a period being discovered and a great many await future investigation.

TABLE I

Star	R.A. 1900	Dec. 1900	Type		V ₀ Calcium	V ₀	V.	P Days	K Pri- mary	K Ca.	
			I	II							
1 Boss 46....	00 12.4	+50 53	A	B2	-23.5	-44.9	-7.0	3.52	217.4	10	.09
2 χ Cass.	27.3	+62 23	B	Bo	-16.8	-3.0					
3 Boss 443	01 52.9	+75 01	Ao	B5							
4 α Persei.	03 38.0	+31 58	B1	B1	+12.4	+18.5	+6.5	4.42	111.9	0	.0
5 ξ Persei.	52.5	+35 30	Oe5	Oe5	+15.4	+65 \pm	+6.2	6.95	?	8	.03
6 η Camel	04 44.1	+66 10	B	Bo	2.2	+6.3					
7 ϵ Orionis	45.9	+5 26	B3	B3	-16.1	+23.3	+15.4	9.59	25.9	21 \pm	.03
8 η Orionis....	05 19.4	-2 29	B1	B1	?	+35.5	+16.9	7.99	144.8	?	.02
9 ψ Orionis....	21.6	+3 00	B2	B2	+13 \pm	+12.0	+17.4	2.52	144.1	80 \pm	.06
10 χ Aurigae....	26.2	+32 07	B1	B1	-1.5	-0.1	+9.1	655.2	20.5	10.5	.17
11 δ Orionis	26.9	-0 22	B	Bo	+18.7	+15.2	+17.1	5.73	100.0	00	.08
12 ν Orionis..	29.0	1 13	B3	B3	+14.4	+21.0	+17.1	1.49	132.4	5 \pm	.0
13 ϕ Orionis....	29.3	+9 27	B	Bo							
14 θ Orionis....	30.5	5 29	B1	B1							
15 ϵ Orionis	30.5	5 29	Oe5	Oe5	-30.1	+21.3	+15.9	29.1	109.9	0 \pm	.75
16 ϵ Orionis	31.1	-1 16	B	Bo							
17 μ Camel	06 23.0	+20 17	B5	B5	+16.9	-38.5	+12.7	3500.	30.	?	.20
18 η Camel	40.5	+67 41	B3	B3							
19 29 Cen. Maj	07 14.0	-24 23	Oe	Oe	?	-12.1		4.39	218.4	?	.16
20 50 Cen. Maj	10 16.9	+66 04	A	A				11.58	36.1	36.1	.35
21 ρ Leonis..	27.5	+9 49	Bp	Bp	+10.0	+43.2		12?			
22 θ Virginis....	13 04.8	-5 00	A	A							
23 β Scorpii....	15 59.6	-19 32	B1	B1	-12.4	-8.5	-10.9	6.83	126*	10 \pm	.27
24 σ Scorpii	06 15.1	-25 21	B1	B1							
25 β Lyrae	18 46.4	+33 15	B2p	B2p				12.92	184*	184 \pm	.02
26 Boss 4870...	19 03.1	+41 16	A	B2							
27 σ Aquilae....	34.3	+5 10	B8	B5	12.6	-5.0	-16.7	1.95	163.5*	0 \pm	.0
28 Boss 5070....	19 47.2	+40 20	A	B3							
29 Boss 5150....	20 00.7	+31 56	G	B2							
30 Boss 5236....	20.0	+37 10	A	B							
31 γ Cygni	48.1	+34 17	A	B2	-11.0	-49.1		3.00	224*	0 \pm	.0
32 H.R. 8427...	22 02.0	+47 45	A	B2	-1.5	-17.8	-14.0	2.17	127.7	0	.0
33 12 Lacer....	37.0	+39 43	B2	B2	8.0	-8.5		0.19	var.	var.	.0
					-17.7	-19.1					
34 Boss 5918.	52.7	+48 09	B3	B3							
35 H.R. 8800.	23 02.7	+45 33	A	B3	-8.3 \pm	-16.2		3.34	88 \pm	0.0	.23
36 H.R. 8803.	03.0	+59 13	B2	B2	-9.0	-7.5	-10.7	7.25	39.0		.39
37 Boss 6142.	23 50.5	+56 53	Bp	Bp	-24.0	-26.7		13.43	115.5*	0 \pm	.10

The first four columns of the table need no explanation. Column five gives the type of spectrum as listed in H.R. 50. Column six gives a corrected type, based on either later determinations such as the revised Draper catalogue, the Mount Wilson Publications, or the spectrum has been examined here. Column seven gives the velocity of the centre of gravity of the system as determined from the calcium lines H and K if an orbit was based on these or the mean velocity found for them if they were treated as constant. In all cases this has been reduced to the wave length 3933.825 for the K line. The velocity of the system as determined for the other lines in the spectrum is found in column eight and the ninth column gives the velocity of the solar motion toward the star. The remaining four columns give approximate data relative to the orbits and are readily understood from the headings. In the column giving the semi-amplitude K, those which are marked with a * show a secondary spectrum.

Spectral Type

Considering the relative numbers of B-type stars in column five to stars of later types, one would suspect that the stationary calcium lines had a tendency to occur in the early types. This fact was first mentioned, I believe, by Jordan⁷ and commented on by the writer also⁸. The types in column five, especially toward the end of the table, would seem to question this relationship but the next column where the types have been corrected leaves no doubt on the question. It seems remarkable that out of 37 listed examples so many should be in error in type of spectrum and it makes one wonder whether there are not more B-type spectra among the faint stars than at present supposed, for it is faint spectra that are most liable to be misjudged. In examining column six we note that there are two A-type spectra but neither of these stars should be listed in the table.

The first is 30 Ursae Majoris (R.A. 10^h 16.9^m). It was announced as a binary in the publications of the Allegheny Observatory⁹. Considerable difficulty was encountered in getting a satisfactory orbit and the one given in the reference above was determined for the hydrogen and calcium lines separately. As these showed a small difference in range, the star has been usually classed as belonging to the list of stars with peculiar calcium lines. The orbit has been reinvestigated by Schlesinger¹⁰ and he finds that the two hydrogen lines differ more from one another than either do from the K line. The conclusion is that there is no abnormal behaviour in the calcium lines.

In the second case, θ Virginis (R.A. 13^h 04.8^m) the data are very meagre. It was published as a binary by Mitchell in the *Astrophysical Journal* Vol. 30. Eleven plates were taken and these show a range for the hydrogen and helium lines from -6 to $+16$. The calcium lines were measured only on three plates. On the first K gave $+14.6$, while the whole plate gave -1.4 . On the second plate K gave $+5.2$ and the whole plate $+4.3$, while the corresponding values for the third plate were -6.7 and $+7.3$. The range in the calcium is about the same as the other lines. Bearing in mind the uncertainties of single line velocities the star need not weigh very heavily as evidence until investigated further.

Leaving 30 Ursae Majoris, and θ Virginis aside practically all the stars are of type B2 or earlier, but too much stress should not be placed on the exact subtype number. Any one who has examined B-type spectra realizes the difficulties in a natural classification. In the first place in some stars the lines are so faint and diffuse as to be almost invisible while in others the lines are beautifully sharp and narrow. The Draper classification nominally at least is based on the relative intensities of the lines. When the lines are sharp and narrow they are easily seen and the criterion is quite definite, but among the very poor lined stars the exact classification is more difficult. The line 4267 assigned to carbon is quoted as appearing in B2 spectra but absent in B3. If we make this a deciding point several of the stars listed as B3 would drop back to B2. In any case it seems that the phenomenon is connected with stars of early type rarely as late as B3 on the Harvard scale. This fact makes it almost certain that the calcium vapor causing the absorption is connected with the star. That is, there is a stage in the effective age of a star at which it shows the stationary calcium lines and this stage occupies a comparatively short interval of the time scale in the star's life.

All the stars listed in Table I are north of -20° declination. If we list all the stars of type B2 or earlier given in H.R. 50 and above the same declination we find we have information on only fifty. Fourteen seem to give constant velocity. In these cases it is impossible to investigate the behaviour of the calcium lines. In all those for which an orbit has been published and the H and K lines investigated the latter have been found either to be stationary or to yield a range less than the other lines.

At the present time it would be safe to say that if a star is a spectroscopic binary and shows calcium lines giving a smaller range than the other lines, it will be B3-type or earlier and conversely if a star of B2-type or earlier is found to be a binary, the calcium lines will give a smaller range than the other lines. The converse statement needs to be qualified slightly. There are several stars listed as B2 which have very wide and diffuse lines and in which the K line is also very poor and hence it has not been investigated separately. α Virginis is an example of this class. The problem of the wide and diffuse character of the spectral lines in some of these stars is a much wider one than that of the stationary calcium lines. It comes up not only in B-type spectra but also in stars of A- to F-types and even in still later types. It probably is connected with the motions and conditions of the gases in the reversing layer while the stationary calcium lines have their origin outside this region, and if this is the case the fact that we observe many stars at present listed as B2 which have no sharp K line would show that there are stars of early B-type without the calcium envelope.

Theories to Account for the Phenomenon

Hartmann in his original paper on δ Orionis put forward three hypotheses to explain his results. The first hypothesis was that the upper atmosphere of the earth contains calcium sufficient to produce the narrow line. He did not suggest this seriously and at once ruled it out because in that case the line should be present in all stars. A second suggestion that the narrow lines had their origin in a very massive secondary surrounded

by a calcium atmosphere can hardly be said to be much easier to accept. The difficulties that beset this interpretation occurred to Hartmann and among others he mentions the great mass necessary to assign to the secondary and its peculiar spectrum consisting of the two lines H and K. He, therefore, proposed the theory that the absorbing gas is "not in immediate connection with the star" and he follows this with the further addition that the cloud lies between the star and the observer.

Shortly after the appearance of Hartmann's paper, Julius¹¹ suggested that δ Orionis was not a spectroscopic binary and that it was surrounded by a large tenuous cloud of calcium vapor. The rarity of the atmosphere accounted for the narrow absorption lines while the apparent irregularities in the other lines were due to what he called "anomalous refraction." The great number of subsequent discoveries of stars with fairly sharp lines which show large periodic displacements and some with both spectra visible and eclipsing variables leave no doubt whatever the stars are genuine binaries and that Julius' theory, however efficacious it may be in explaining irregularities in the character of the lines, can not overcome the difficulty of explaining the oscillating lines. Almost everyone who has worked in this field is convinced to-day that the stars are binaries and that the narrow H and K lines have their origin in a cloud at low pressure.

There are three distinct ways in which we may regard the calcium cloud as causing the presence of the H and K lines in these stars. First, Hartmann's suggestion that the cloud lies between the observer and the star. Second, the nebulosity surrounds the star but is not an integral part of it, being in the nature of the diffuse nebulosities that we can photograph in the background of the sky in several regions where the B-type stars are numerous. Third, the calcium cloud is a part of the star's atmosphere but possibly much more extended than the reversing layer proper. We will consider the difficulties connected with these theories in turn.

First Hypothesis. The great objection to Hartmann's suggestion is, that so far all the stars that show the phenomenon are of one spectral class. In this regard it might be urged possibly that the B-type stars being so very distant are beyond certain nebulosities in the Milky Way while stars of later type are nearer and accordingly escape showing the calcium absorption. This method of avoiding the difficulty can hardly be resorted to in considering the stars of early and late B-type.

In figure I are plotted all the stars showing the stationary calcium lines. They are plotted as round black dots. Only the northern hemisphere is shown as data is at hand for this hemisphere only. The B3 and B9 stars are also plotted as small crosses and these are found in the same general regions. If Hartmann's theory were correct it would seem that we should find more cases among the late B-types than among the early for they outnumber the latter very much. The fact that we do not argues very strongly against the theory and it also argues against the second hypothesis for both the early and late B-types are found scattered through the same regions and only the early types show the phenomenon of stationary calcium lines.

The agreement between column seven and column nine in the table of stars has been urged as showing the calcium vapour to be of a nebulous nature and at rest in space. Why should we regard it at rest? As a matter of fact the difference for several stars is

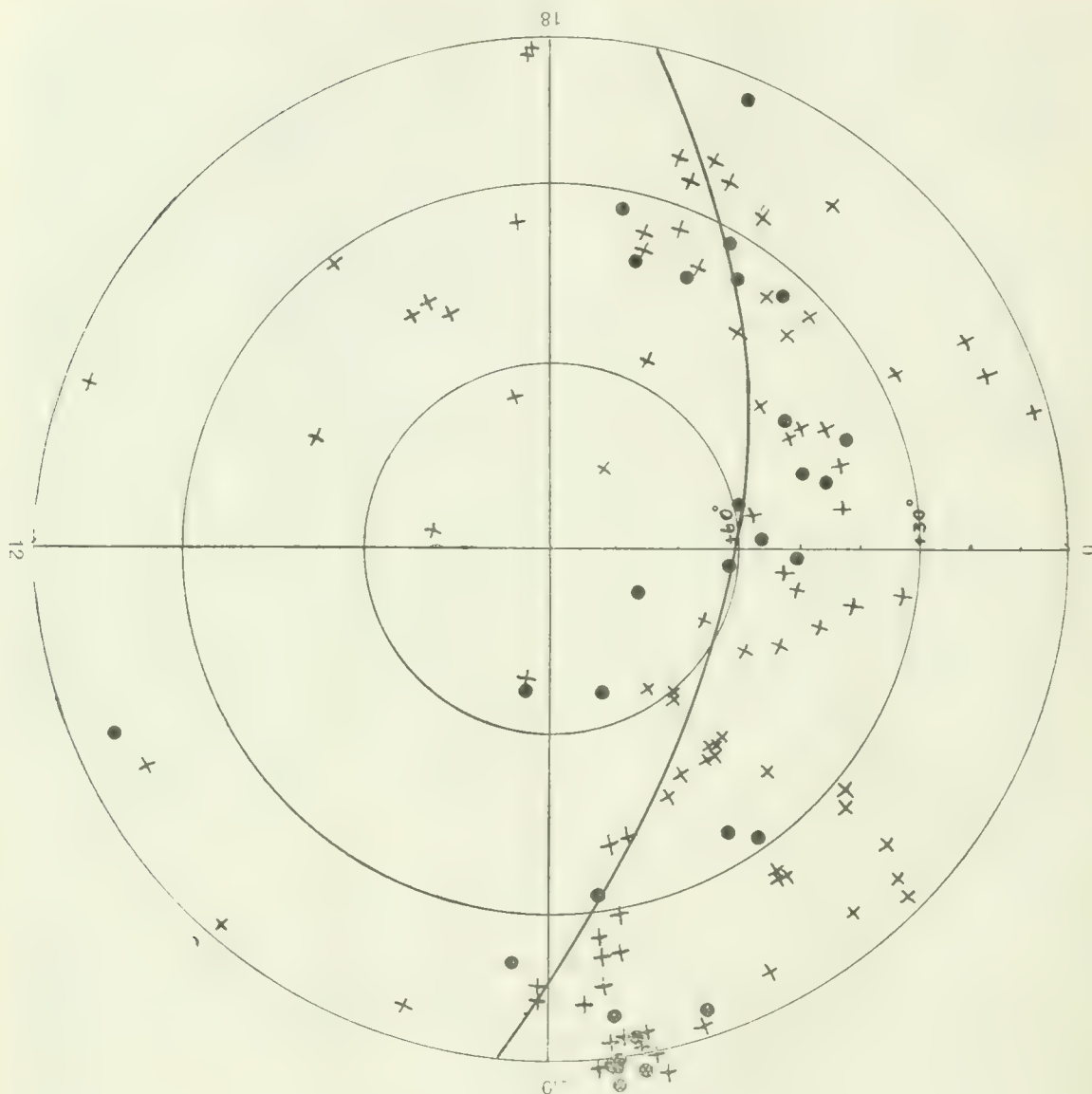


Fig. 1

large. For Boss 46 it is over 16 kilometres, for ι Orionis it is over 14 kilometres and in H.R. 8427 it is over 15 kilometres. Agreement or disagreement lends little weight to the argument either way and in view of other objections Hartmann's suggestion can not be accepted.

Second Hypothesis. We believe also that this hypothesis, that it is the diffuse nebulosities which are responsible for the calcium absorption, is not correct. We mentioned before that the similar distribution of early and late B-type stars was an objection to it. The Pleiades also afford evidence to the contrary. These form a group of stars well known to be surrounded by a nebulous cloud and the stars do not show a

narrow and sharp K line. All the lines are wide and diffuse. The stars are mostly of B5-type. An important observation bearing on this subject has recently been secured by H. H. Plaskett. Spectrograms of two early type stars only a few seconds of arc apart show quite different calcium lines. The earlier type shows a fine sharp line and the other a somewhat later B-type shows quite an ordinary K line. Now that the Draper Catalogue is so near completion, it should be possible to find more pairs of stars of this nature.

Third Hypothesis. The third hypothesis, that the calcium cloud is a part of the star's atmosphere seems most satisfactory to the writer and the following facts may be adduced in support. There is concrete evidence in the case of 12 Lacertae that the calcium is closely associated with the star. 12 Lacertae was discovered by the writer to have a period of about four and one-half hours and the calcium lines give about half as large a range as the other lines. The velocity of the system as determined from the H and K lines agreed with the velocity of the system for the other lines but series of plates taken in consecutive years showed both to be varying. The values so far are

	1913	1914	1915	1918
Hydrogen and Helium...	-8.5	-11.2	-15.6	-19.1
Calcium.....	-8.0	-9.1	-11.2	-17.7

We must conclude that the calcium vapour causing the absorption is moving with the star and also that it is so limited in extent that it surrounds the origin of the short period variation whether we regard it as a binary or a pulsating nucleus but does not extend to the distant companion which presumably is the cause of the variation of the centre of mass. H. H. Plaskett's observation showed that the cloud must have an apparent diameter of less than a few seconds but it would further appear as if the angle at the observer is extremely small. On two occasions the writer exposed a plate in the spectrograph for about ten times the normal exposure time, keeping the star image as stationary as possible on the slit and behind a small strip of paper which cut off about two seconds of arc. The idea was that if an extended atmosphere existed it might record as a bright line outside the region of continuous spectrum. The result was entirely negative although possibly this was to be expected in view of the probably very faint emission.

There is a fact which at first sight seems contradictory to this third hypothesis. The velocity as given by the calcium lines is usually not in agreement with the velocity of the system as derived from the other lines and up till recently the investigated orbits gave values which agreed quite closely with the component of the sun's motion toward the star. The data are set forth in columns 7, 8 and 9. Column 7 gives the velocity derived from the calcium lines. This depends so far as the writer was able to reduce the observations on the wave length 3933.825 for K. Column 8 gives the velocity from the lines of helium, hydrogen, carbon or whatever other elements were present and the ninth column gives the velocity of the sun toward the star. It is the discordances between columns 7 and 8 which have been taken to indicate a separate origin for the calcium. Obviously the velocity obtained depends on the wave length adopted and when velocities from two lines or sets of lines differ we can make them agree by altering the wave length

of either the one or the other. In the spectrum of P Cygni¹², Merrill found that the silicon lines were displaced one-fourth of an angstrom unit to the red when the other lines in the spectrum were taken as standard yet no one suggests that the silicon is due to an intervening cloud. Albrecht found that the wave lengths¹³ varied with the type and apart from this systematic tendency there are undoubtedly individual discordances which in some cases amount to twenty kilometers. The question of the wave lengths of the lines in stellar spectra is very complicated and one about which we know very little in comparison to what is yet to be learned. It seems to the writer that, judging from the irregular manner in which wave lengths of stellar lines shift from star to star, we are quite justified in assigning the differences between columns 7 and 8 to the selection of the wave lengths upon which the velocities rest.

All the difference may not be due to variations in the wave lengths of the calcium lines. In fact it would seem that most of it should be assigned to variations in the other lines of the spectra. The reason for this is two-fold. Firstly, the calcium lines are sharp and narrow and presumably have their origin in gases at a low pressure and so are less likely to be affected by disturbing influences. Secondly, the velocities from the calcium lines are more in accord with what we expect velocities of B-type stars to be. Take for example ϕ Persei. If we take the helium lines we get an apparent velocity +65 km. or nearly 60 km. for the space velocity while the calcium lines give quite a normal result. Compare also ρ Leonis and Boss 46. In general also though not always those stars which show the greatest difference between the two velocities are the ones with the broadest and most diffuse hydrogen and helium. (cf. Y Cygni). It is possible that the conditions which broaden the lines may also shift the centre.

A consideration of the novae would seem to throw some light on these two hypotheses. Most astronomers, I believe, incline toward the collision theory for the origin of new stars. A comparatively faint star in its journey through space runs into a nebula and the friction heats the star so that its light increases several magnitudes. When we consider that the nebulae have actually been photographed surrounding these stars and also that the lines of both sodium and calcium are sharp and narrow the connection between the novae and stars showing stationary calcium lines looks pretty certain. These are, however, fatal objections to making the case of the stationary calcium lines similar to the novae. Firstly, the early B-type stars have a stable spectrum which in other respects is not like the novae spectrum and secondly their light is constant. They are, therefore, not drifting through the nebula. It is much preferable to suppose that in the rapid gamut of types through which the nova spectrum runs, *whatever be the cause*, it inevitably passes through the sharp H and K stage in the same way as possibly all stars will do or have done if they come to the B-type stage at all.

Accepting the hypothesis that the calcium vapor is a part of the true atmosphere of the star we must find some way of explaining the stationary character of the lines. In 1915¹⁴, the writer tried to show in a general way how this might come about from a large envelope enclosing the two nuclei, the whole rotating with the period of revolution of the two stars. This explanation breaks down when examined quantitatively and it seems necessary to suppose that the outer layers of the calcium are not rotating as fast as the period of revolution.

In determining the orbit of σ Aquilae¹⁵ Jordan found that in addition to the stationary K on some plates there was another line near K whose position when measured was seen to coincide very nearly with one of the components. Later, finding it on several plates, he was led to re-examine plates of other binaries and he found strong evidence of the same thing in VV Orionis, β Scorpii, and especially in α Persei. The lines were very faint and Jordan does not think the evidence absolutely conclusive. H.R. 8803 whose orbit is now being investigated at this observatory by S. L. Boothroyd, shows evidence of the same thing. This is a very important result and one worth settling with finality one way or the other. Plates should be taken at times when the components would be separated using fine grained plates and narrow slit so that if possible the presence of the faint lines could be made certain.

Working Hypothesis. In view of all the facts in the preceding paragraphs, the following working hypothesis is proposed for the origin of the calcium lines. All the early B-type stars are supposed to be surrounded by an envelope which is not a part of the reversing layer in which are found hydrogen, helium and other elements. Nevertheless, the envelope is not the extended nebulosity observed in the regions where these stars abound but it subtends at the observer a small and at present unknown angle. It occurs at a definite time as a stage in the life history of the star and gives rise to the sharp H and K lines and the D_1 and D_2 lines which will be stationary if the star is a binary. It is not clear whether the envelope is due to condensation of the extended nebulosities or comes from the star. One would favor the view that at first the cloud was the extended nebulosity and that in this condition it does not absorb sufficiently to give rise to the K line. The calcium line in the reversing layer proper is also supposed to be very faint so that at this stage we would have those stars which give practically no K line at all. A later stage, as the surrounding cloud grows more condensed would be the sharp H and K stage, the calcium line in the reversing layer being very faint still but growing stronger. This component is supposed to oscillate with the period of the binary and at first it manifests itself as giving to the measures of the blended K line, a small range which increases as the component in the reversing layer grows stronger. This stage is approximately B0 to B2. A still later stage makes the line in the reversing layer predominant and the calcium lines then take on all the characteristics of the other spectral lines. This stage is reached as a rule by the time the star is B3-type. It is quite probable, however, in view of the present bright lines visible in late B-type stars and other anomalies that when the true line of evolution for these stars is known, the subtype numbers may be shifted around considerably and we think that those stars which show the stationary calcium lines may form a class.

Observations Required. In attempting to form a program for attacking the problem of the stationary H and K lines several points and needs must be borne in mind. The addition of new orbits, in which the calcium lines give constant velocities, can add but little to the solution. Nevertheless, it is necessary to determine as many as possible in the hope that some feature but dimly shown in the majority will be prominent enough in some future star to be noticed. We refer to such characteristics as that discovered

in σ Aquilae. Again some stars about which there seems to be nothing abnormal need not receive particular attention but those which already show peculiar and unexplained detail should be examined exhaustively. The table of stars will afford several stars of this nature. Many of the early results on B-type spectra were obtained with three-prism dispersion and did not record the results of the K line. There is quite a wide and useful field for the small telescope and instrument in re-examining the bright B-type spectra with special reference to the K line. It will be of interest also to examine stars of Oe- and Od-type and earlier to find out the limit of the class in this direction. Already we have indications that the Oe5 stars as a class have the stationary calcium lines. The relation of mass to the phenomenon may also prove of interest. Ludendorff tabulates in A.N. 5046 the masses of some of these stars and they are very large. Whether this is a true mass relation or whether it is because they belong to the B-type is not quite clear. Some stars of large mass do not have sharp H and K and so far as the evidence goes at present it favors a direct relation between the sharp H and K and the type. While the relation between the mass and the sharp H and K may come from the fact that only the most massive stars reach the B-type.

Dominion Astrophysical Observatory.

Victoria., B.C.

Sept. 1920.

NOTES TO TABLE 1.

1. The orbit for this star is published in Ap. J. Vol. 47, p. 329. The Harvard Photometry gives the type as A, the Mount Wilson photographs as B3p. The New Revised Draper Catalogue calls it Bo. The hydrogen and helium lines give a range of 450 km. The calcium shows a range of 20 km. All the lines are faint and diffuse save the H and K which are sharp and narrow.

2. κ Cassiopeiae was announced as binary by Campbell, L.O.B. 199. No orbit has yet been published. The results on the table are taken from the Dominion Observatory Publications Vol. 4, p. 309. The spectrum shows the two silicon lines 4552 and 4567 in addition to the usual lines. All the lines are fairly sharp.

3. Three plates taken at this observatory by Harper are all the data available for this star and the type B5 is judged from an examination of them. All the lines including K are rather wide. Harper's measures give a range of about 85 km. for the hydrogen and helium while the calcium K seems to give a very much smaller range.

4. This star was discovered to be a binary at the Yerkes Observatory and announced in the Ap. J. Vol. 15, p. 214. A preliminary curve was determined by Vogel, Ap. J. Vol. 17, p. 212. The present results are taken from the Allegheny Observatory Publications Vol. 2, p. 63 by Jordan. Both spectra are visible. The lines are of rather poor quality but better than the rule in stars of this type which show a large range. The calcium lines are sharp and narrow. Jordan's results give the velocities of the calcium lines as stationary. A re-examination of the plates later in connection with the orbit of σ Aquilae showed a second K line which oscillated with the hydrogen and helium lines.

5. The hydrogen and helium lines in this star are extremely wide and diffuse and no orbit has been determined from them. In the Jour. R.A.S.C. Cannon publishes an orbit from the H and K lines which are sharp and narrow. The range is only 16 km. On some of his sheets, which were placed at the writer's disposal while at Ottawa, measures were shown of the other lines. They seem to show a very wide range and the mean seems to be very much higher than +15 km., probably +65 km.

6. The only orbit published for this star rests on the Calcium lines, Ap. J. Vol. 37, p. 1. It seems to the writer that until further investigated it would be unwise to use the elements in statistical investigation. The range of the hydrogen and helium lines, which though quite broad are measurable, is small. The calcium lines are sharp and strong and there can be no doubt of the reality of the variation indicated. The shape of the velocity curve is unusual and the observations do not fit the computed curve at all well.

7. π^4 Orionis was announced as a binary by the Lick and Yerkes Observatories L.O.B. No. 31, 1902 and Ap. J. Vol. 17, p. 153. The spectroscopic orbit was published by Baker in Publications of Allegheny Observatory Vol. 1, p. 107. All the lines are of good quality and it was only on re-examination of the data that it was discovered that the calcium lines gave a range about ten kilometers less than the other lines. The hydrogen and helium lines give a range of 52 km.

8. In the orbit of the star published by Adams in Ap. J. Vol. 17, p. 71 no mention is made of the calcium lines and presumably his spectra did not extend to that region. The lines are of good quality and show a range of nearly 300 km. Campbell in his second catalogue quotes a private letter from Slipher announcing H and K sharp and yielding constant velocity.

9. The lines of this star are rather wide and diffuse but seem to be somewhat better than the average where there is such a large range in the radial velocity curve. In the orbit published by Plaskett no mention is made of the H and K lines and apparently they were not measured. Harper from 16 measures (D.O.P. Vol. IV, 343) of the calcium lines finds they indicate a range of 80 or 90 km. The hydrogen and helium lines give a range of 300. Campbell in the second catalogue of binaries quotes a private letter from Baker stating that two spectra are visible and $m, m = 0.76$.

10. An orbit of this binary was published by the writer in the Jour. R.A.S.C. Vol. 10, p. 370. It is remarkable in the length of the period, 655 days. The lines are all sharp and narrow and the calcium lines give a range of 20 km. which is about one-half the range for the other lines. Rufus in Jour. R.A.S.C. Vol. 14, p. 139 finds some evidence that the hydrogen gives a smaller range than the other lines due to helium, silicon, etc. At the time of publishing this orbit I took the means of all the elements separately and concluded from the same data that calcium was the only one that showed the effect. There is a peculiarity in the appearance of this star which was not mentioned in the published orbit. To the writer it has always appeared distinctly yellow or whitish in color. It would be of interest to determine its color index.

11. δ Orionis was the first star discovered in which the calcium lines gave a velocity different from the other lines. Recently Hiss Heger has discovered that the sodium lines are also sharp and narrow and give constant velocities. The lines are of fairly good quality and the secondary does not show. Two orbits have been published. The first by Hartmann in Ap. J. Vol. 19, p. 268 and the second by Jordan in the Publications of the Allegheny Observatory, Vol. 3, p. 125.

12. This star is an eclipsing variable. Daniel in his published orbit, Allegheny Observatory Publications, Vol. 3, p. 179, finds that there is no trace of the secondary on Seed 23 plates taken for the special purpose of finding it. The lines are rather broad and diffuse but fair. There is evidence of a long period oscillation of about 30 km. amplitude and 120 day period. The calcium lines are not quite fixed but seem to have an oscillation of about 10 km. amplitude. Jordan in connection with an orbit for σ Aquilae finds evidence for this star of the presence of a second K line which shifts with the hydrogen and helium.

13. Very little has been published about this star. In Ap. J. Vol. 30, p. 63 Frost and Lee give the results of the measures of 6 plates. The hydrogen and helium give a range of 12 km. with a mean velocity of +40. Calcium shows a range of 34 km. with a mean of +20. All the lines are very sharp and narrow.

14. Announced as a binary by Frost and Adams in Ap. J. Vol. 19, p. 153. The hydrogen and helium lines are broad and diffuse. They seem to give a range of about 140 km. No mention is made of the H and K lines. It is included in the Lick Observatory list of stars showing peculiar behaviour of calcium lines, Vol. 13.

15. An orbit of this spectroscopic binary is published by Plaskett and Harper in Ap. J. Vol. 27, p. 272. The lines are rather wide and diffuse and though not mentioned the calcium lines are presumably not very sharp and narrow or they would have attracted attention. Slipher in a letter to Campbell for the Second Catalogue mentions H and K as giving constant velocities and Harper from the result of 30 plates (D.O.P. Vol. IV, 345) finds γ for calcium +30.1. There is some evidence of the presence of the secondary spectrum.

16. The results for this star are published by Frost in the Ap. J. Vol. 29, p. 235. Hydrogen and helium are broad and diffuse while H and K are sharp and narrow. Fourteen one-prism plates were secured. The variation indicated is small and the evidence so far as it goes seems to show that the range of the calcium is as large as that of the other lines.

17. ν Geminorum was announced as a binary by Lee in Ap. J. Vol. 32, p. 301. The measures indicate that the calcium lines give velocities differing from the hydrogen and helium lines. A large amount of work has been done on this star at Ottawa by Harper, Jour. R.A.S.C. Vol. 13, p. 179. He finds the calcium lines are rather poor and that the hydrogen and helium lines have a sharp core which gives a period of oscillation of 9.6 years not shown by the calcium lines. There is a short period oscillation as well. Until this short period oscillation is determined and the relation of the calcium lines shown to it we can hardly say whether the star should be included in the class of binaries showing peculiar behaviour of the calcium lines.

18. Scarcely enough is known about the spectrum of this star to justify its being included in the list. It is announced as a binary by Lee in *Ap. J.* Vol. 32, p. 302. The hydrogen and helium lines seem to be complex and on the two plates on which H and K were measurable they gave velocities +17 and +17 as opposed to a mean velocity for the other lines from 5 plates of -4.

19. An orbit for 29 Canis Majoris is published by Harper in the Dominion Observatory Publications Vol. 4, p. 115. The range is over 450 km. and the lines fair. No mention is made of a secondary spectrum and the lines are of fair quality. On only 4 plates was K measurable but he remarks that it does not share in the large range of the other lines.

20. 30 Ursae Majoris should not be included in this table and it is so only because included in former lists. Later investigation has shown that there is nothing peculiar in the behaviour of the calcium lines. (cf. *All. Obs. Pub.* Vol. 1, p. 121 and Vol. 2, p. 29).

21. The results for this star are published in Dominion Observatory Publications, Vol. I, p. 351. From 65 plates Harper was unable to find a period. All the lines are fairly sharp and narrow and the two lines of silicon 4552 and 4567 are prominent. From a consideration of the residuals Schlesinger concludes that the period is in the neighbourhood of 12 days. (cf. *Ap. J.* Vol. 41, p. 166).

22. Very little is known about the calcium lines in the spectrum of this star. Its spectrum consists of many sharp and well defined metallic lines, typical of A2-type.

23. Two orbits are published for β Scorpii, the first by Duncan in Lowell Observatory Bulletin No. 54, the other by Jordan in Allegheny Observatory Publications Vol. II, p. 137. There is quite a large difference in the two orbits for the velocity of the system and also a difference in the mean velocity for the calcium lines. There seems to be a small amplitude for the calcium lines. The lines are rather broad and diffuse and the secondary component is present. In connection with an investigation of σ Aquilae Jordan finds that there is an oscillating K line as well as the stationary one.

24. The orbit for α Scorpii has been published by Selga and also Henroteau, in the Lick Observatory Bulletins. Two periods are present, a six hour one and a 34 day one. In the publication referred to no mention is made of the K line but in a later Publication Dominion Observatory, Vol. V, No. 1, Henroteau mentions the K-line as being stationary. It would be interesting to investigate its behaviour with reference to the double period.

25. Publications of the Allegheny Observatory Vol. II, p. 98 contains a long discussion of the results of the investigations on this star whose spectrum contains several sets of lines. The calcium line K was measured in the B8 spectrum and in the B5. The B8 lines oscillate with a range of about 200 km. and no mention is made of the calcium having a range different from the other lines. The B5 lines give zero range of velocity and the calcium line in this group agrees with the velocity of the system.

26. This star was announced as a binary by the writer in the Jour. R.A.S.C. Nov. 1918. The lines are sharp and narrow and while the data is hardly sufficient to be conclusive yet the present indications are that the calcium lines give a smaller range than the other lines.

27. The spectrum of this star is listed as B8. In a determination of the orbital elements (cf. *Publ. All. Obs.* Vol. III, p. 189) by Jordan the line 4267 is listed as present and 4481 is very faint. It would seem, therefore, that the type should be B3 or earlier. All the lines including K are diffuse and difficult to measure. Two components are visible and Jordan makes the interesting discovery that on 10 plates near the calcium line K there is another line presumably a second calcium line which oscillates with the hydrogen and helium lines.

28. There is no orbit published for Boss 5070. Harper has the results of measures in press and from several plates he finds that H and K do not share in the large oscillation of the other lines.

29. Boss 5150 was announced as a binary from the Mt. Wilson Observatory and independently discovered as a binary here. Both observatories noted that the calcium lines differed in behaviour from the hydrogen and helium. The star is under investigation.

30. Very broad hydrogen and helium lines in this star. The calcium line K is sharp and gives a smaller range than the other lines. Both spectra show on two plates and on one plate K is doubled. It was announced from this observatory in the Jour. R.A.S.C. Nov. 1918.

31. This star is an eclipsing variable. Its spectrographic orbit has been determined at this observatory by the director and the spectrum listed as A is really B2. The calcium lines are sharp and narrow and give nearly constant velocities. Both spectra, consisting of very broad and diffuse lines, are present.

32. The writer has an orbit for this star in press. All the lines are wide and diffuse save K which is fair and gives a constant velocity. The secondary spectrum was not measured on any of the plates though its presence was suspected. The spectrum is approximately B2.

33. An interesting feature of this star is that the velocity of the centre of mass seems to shift progressively, ranging from about -9 km. in 1913 to -19 km. in 1918, and the calcium lines, which give only about half the range that the hydrogen and helium lines do, show a mean velocity which agrees from year to year with the velocity of the center of mass. All the lines are of about the same character being usually sharp and narrow but they vary in character as does the amplitude of the radial velocity curve derived from measures of them. (cf. Jour. R.A.S.C. Vol. 13, p. 54).

34. This star was announced as a binary by this observatory in Jour. R.A.S.C. Nov. 1918, from 4 plates. All the lines are fairly good, the hydrogen and helium give a range of about 40 km. and the present indications are that the calcium lines will show a smaller amplitude.

35. An approximate orbit for H.R. 8800 has been completed by the writer but not yet published. The lines are of rather poor quality and K is not very good though better than the other lines. It seems to give an almost stationary velocity.

36. H.R. 8803 was announced as a binary from this observatory in Jour. R.A.S.C. Apr. 1919. Measures of six plates gave a range of 100 km. for the hydrogen and helium lines while the calcium K gives a smaller range. All the lines are fairly sharp and narrow. There is some evidence that there are two K lines.

37. The lines in this star are wide and diffuse except K which is very sharp and narrow. An orbit was published by the writer in Jour. R.A.S.C. Vol. X, p. 297. The calcium lines are stationary and the secondary is present but not sufficiently strong to measure.

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- 9 Pub. Alleg. Obs. 2, 121
- 10 Pub. Alleg. Obs. 2, 139
- 11 Ap. J. 21, 286
- 12 Lick Obs. Bull. 6, 156
- 13 Bull. of Nat. Obs. Argent. No. 1
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- 15 Pub. Alleg. Obs. Vol. III, 189.

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ORBIT OF THE SPECTROSCOPIC BINARY H. R. 6169

BY REYNOLD K. YOUNG

H. R. 6169 (R. A. 1900, $16^h 30.9^m$, $\delta = + 17^\circ 15'$) was announced as a binary in 1919 by the writer from 4 single-prism plates. These spectra showed a range of about 60 kilometers and the lines looked fairly sharp. Thirty-eight additional observations have been secured with a view to determining the orbital elements. On many of the later plates the secondary component is plainly visible though very much fainter than the primary, the ratio of intensities being about 3 to 1. When the lines are superimposed, the spectrum shows a fairly good A₀ type spectrum, many of the iron lines, such as 4045, 4063, 4071 and other metallic lines being visible. At other times only the calcium line and the hydrogen series and magnesium 4481 could be measured. The magnesium line in the component spectrum seems to be weaker than the other lines for under all circumstances this line is fairly sharp.

The period was soon found to be approximately ten and one-half days and when the observations are plotted on a single revolution they show that the orbit is quite eccentric and that the observations of the two components are clearly resolved only on one-half of the orbit. The great difference in intensity of the two components makes the measures of the blend follow the orbit of the primary. In the solution for the elements all those observations which showed single lines were assigned to the primary curve and given smaller weight than those observations where the two spectra could be measured. Two plates taken near the crossing point but blended so as to make the lines diffuse were rejected entirely. The measures of the secondary were also included in the solution and given weights as indicated in the table of observations below. The columns are in order, the plate number, the date of observation and the Julian Day, the velocities obtained for components one and two, the number of lines measured and the weights assigned, the phase of the observation using the final period and finally the residuals which the final elements give for the observation. These were determined graphically.

OBSERVATIONS OF H. R. 6169

Plate	Date	Julian Date	Velocity		Lines	Wts.	Phase from 2,422,420	Residuals	
			Comp. I	Comp. II				Comp. I	Comp. II
285	1918 July 1.....	2,421,776.753	+ 2.1		4		0.91	-15.0	
1848	1919 April 21.....	2,070.936	-31.2		6		9.98	+ 5.6	
2062	June 1.....	2,111.836	-56.6		4		8.64	-15.8	
2343	July 13.....	2,153.732	-28.8		4		8.29	+14.0	
4012	1920 April 5.....	2,420.906	- 6.6		4	0	0.906	-23.6	
4030	" 7.....	2,422.934	+47.5	-110.1	3-2	2-1	2.934	+ 1.5	-12
4050	" 9.....	2,424.877	-20.6		6	2	4.877	+ 8.8	
4069	" 10.....	2,425.970	-48.2		4	3	5.970	- 3.2	
4079	" 12.....	2,427.863	-45.2		2	2	7.863	- 1.2	
4091	" 13.....	2,428.963	-35.3		1	1	8.963	+ 2.9	
4145	" 23.....	2,438.905	-25.5	+51.1	7-1	3-0	8.345	+16.5	+ 7
4157	" 24.....	2,439.953	-28.3		2	2	9.393	+ 6.0	
4169	" 25.....	2,440.924	-19.0		7	3	10.362	- 0.4	
4188	" 30.....	2,445.887	-17.4		4	2	4.767	+ 9.6	
4196	May 1.....	2,446.925	-15.1		3	0	5.805	+24.9	
4208	" 2.....	2,447.906	-54.3	+44.8	2-1	2-1	6.786	- 9.5	- 2
4218	" 3.....	2,448.841	-45.4	+52.0	4-1	4-1	7.721	- 0.8	+ 5
4244	" 5.....	2,450.852	-19.2		8	3	9.732	+10.8	
4279	" 12.....	2,457.878	-34.6		3	2	6.198	+ 8.1	
4289	" 13.....	2,458.834	-33.4		2	2	7.154	+11.8	
4304	" 15.....	2,460.813	-28.6		6	2	9.133	+ 8.4	
4314	" 19.....	2,464.817	+63.8	-127.4	6-4	4-2	2.577	- 4.6	+ 9
4331	" 21.....	2,466.822	-26.8		9	3	4.582	- 3.0	
4343	" 24.....	2,469.758	-57.1	+ 33.2	4-1	3-1	7.518	-12.1	-15
4354	" 27.....	2,472.848			5	2	0.048	- 4.5	
4356	" 30.....	2,475.760	+41.2	-103.0	7-5	4-2	2.960	- 3.6	- 8
4368	" 31.....	2,476.779	-19.0		12	3	3.979	-11.0	
4393	June 2.....	2,478.840	-44.3		1	1	6.040	- 2.3	
4404	" 11.....	2,487.814	-23.3		11	2	4.454	- 3.0	
4419	" 17.....	2,493.795	-14.9		5	2	10.435	+ 2.0	
4428	" 18.....	2,494.778	-12.9		5	0	0.858	-27.9	
4435	" 19.....	2,495.843	+81.3	-143.4	5-3	4-2	1.923	+ 9.3	+ 2
4441	" 20.....	2,496.721	+52.2	-109.3	4-3	4-2	2.801	- 2.8	+ 5
4459	" 25.....	2,501.780	-53.6	+ 39.8	2-1	2-1	7.860	- 9.6	- 7
4480	" 28.....	2,504.748	-16.4		9	3	0.268	- 9.6	
4498	" 29.....	2,505.758	+42.3	- 87.5	6-4	4-2	1.278	+ 5.5	- 2
4506	" 30.....	2,506.715	+73.7	-140.5	3-2	3-2	2.235	- 5.3	+15
4508	" 30.....	2,506.751	-87.0	-161.3	7-7	4-2	2.271	- 8.0	- 6
4511	" 30.....	2,506.814	+80.2	-169.2	7-6	4-2	2.334	+ 2.6	-17
4523	July 1.....	2,507.734	+20.7	- 82.5	5-3	4-2	3.254	- 4.3	-16
4656	" 21.....	2,527.767	+78.1	-151.6	6-5	4-2	2.167	- 0.9	+ 3
4740	" 31.....	2,537.787	+52.2	-120.5	8-7	4-2	1.627	- 5.7	+ 2

The early observations are very poorly situated for determining the period accurately. They are shown as solid circles on the radial velocity curve given at the end of the paper, and it can be seen that the last three have scarcely any weight while the first is near a crossing point. This observation has to be brought forward sixty-one revolutions. The

observations in 1920 cover ten revolutions. If we shift the early observation forward to the other crossing point some of the latter observations would be shifted backward nearly half a day and this is not permissible. Hence the early observation is assigned to its correct place and poorly situated as it is, it has more weight in determining the period than the observations in 1920. After allowing for the probable effect of blending the period was fixed at 10.56 days and not included in the least squares solution.

The observations were grouped into the following normal places and preliminary elements selected.

NORMAL PLACES

No.	Phase from J.D. 2,422,420.0	Velocity	No. of Plates	Weight	O - C Prelimin- ary.	O - C Final	pv^2 Prelim.	pv^2 Final
1.	0.092	- 16.3	3	.875	- 3.68	- 3.88	12	13
2.	1.627	+ 52.2	1	.5	+ 2.17	+ 5.66	2	16
3.	1.278	+ 42.3	1	.5	- 9.94	- 5.69	50	16
4.	1.923	+ 81.3	1	.5	+ 5.21	+ 7.86	14	31
5.	2.253	+ 80.8	4	1.875	+ 3.48	+ 1.76	21	6
6.	2.689	+ 58.0	2	1.00	+ 1.51	- 3.34	2	11
7.	2.951	+ 43.3	2	.75	+ 3.48	- 0.73	9	0
8.	3.254	+ 20.7	1	.5	- 1.38	- 4.09	1	8
9.	4.490	- 21.7	12	1.500	- 0.32	+ 0.72	1	1
10.	6.058	- 43.0	3	.75	- 2.71	- 1.42	5	2
11.	6.970	- 43.9	2	.5	+ 0.73	+ 1.44	0	1
12.	7.852	- 44.8	5	1.75	- 0.23	- 0.08	0	0
13.	9.202	- 29.8	3	.625	+ 7.45	+ 6.91	35	30
14.	10.047	- 19.1	2	.75	+ 7.05	+ 6.43	38	31
15.	1.627	-120.5	1	.25	+ 0.85	- 2.07	0	1
16.	1.278	- 87.5	1	.25	+ 2.64	- 0.56	2	0
17.	1.923	-143.4	1	.25	+ 1.79	+ 1.80	1	1
18.	2.252	-155.6	4	1.00	- 8.35	- 1.31	70	2
19.	2.689	-118.1	2	.5	4.17	+ 7.14	8	26
20.	2.951	-105.4	2	.375	-17.54	- 7.97	115	24
21.	3.254	- 82.5	1	.25	-22.66	-16.32	128	66
22.	7.471	+ 42.5	1	.5	- 3.70	- 5.31	7	14

PRELIMINARY ELEMENTS

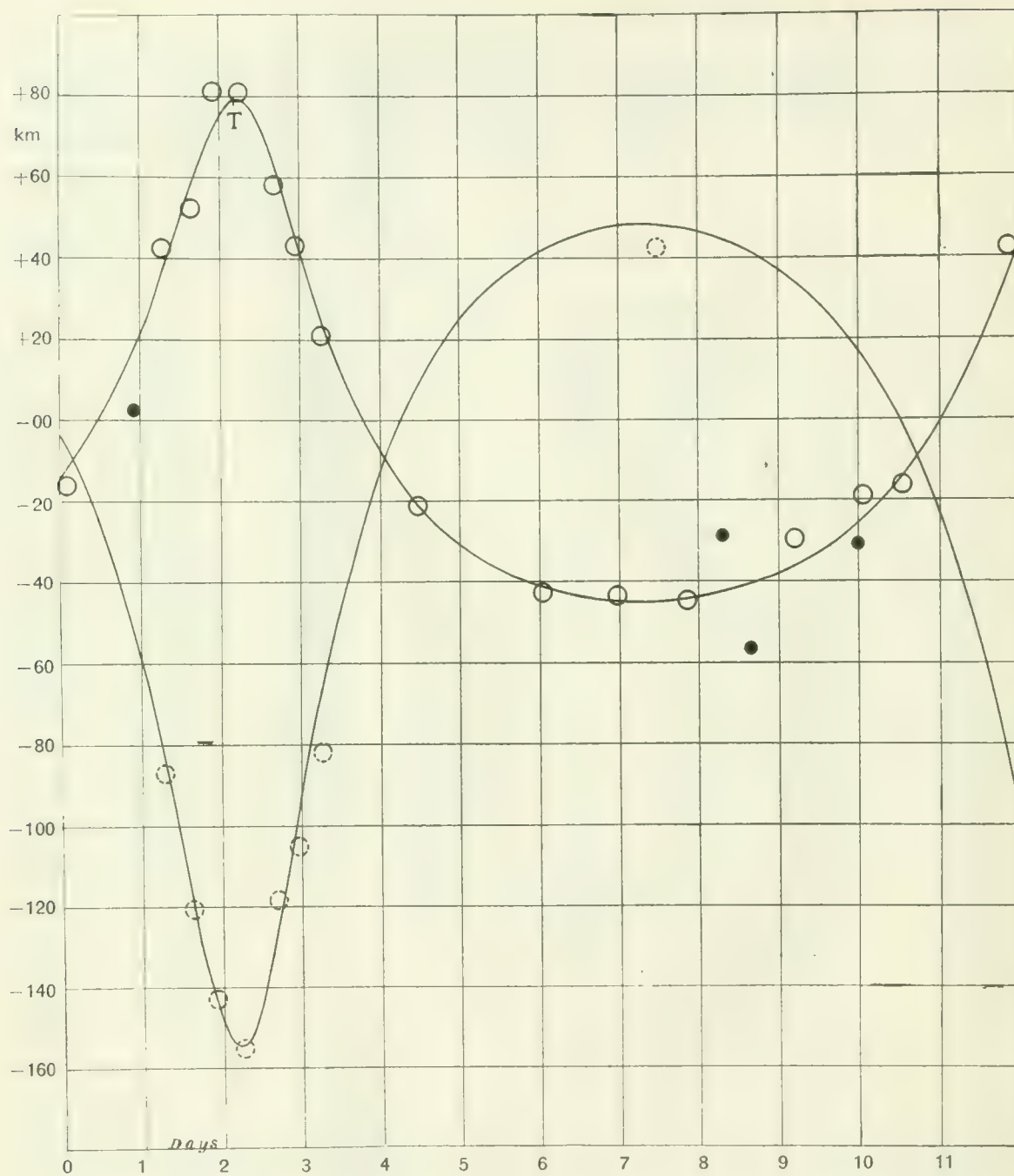
Period	$P = 10.56$ days
Eccentricity	$e = 0.43$
Longitude of periastron	$\omega = 0$ and 180
Semi-amplitude	$K = 62$ km. and 98 km.
Velocity of system	$\gamma = +17$ km.
Periastron passage	$T = \text{J.D. } 2,422,422.112$

The preliminary elements leave the residuals listed in the table of normal places under the heading O-C preliminary. Σpv^2 for the primary component is 190 and for the secondary 331. Observation equations were next formed, both K_1 and K_2 being combined in the same solution as separate unknowns.

OBSERVATION EQUATIONS

1	1.000x	- .078y		- .433u	+ .545v	- .343w	+ 3.68=0
2	1.000	+ .803		- .794	+ .575	- .774	- 2.17
3	1.000	+1.158		- .209	+ .425	- .733	+ 9.94
4	1.000	+1.383		+ .451	+ .188	- .374	- 5.21
5	1.000	+1.403		+ .523	- .143	+ .287	- 3.48
6	1.000	+1.067		- .408	- .478	+ .776	- 1.51
7	1.000	+ .798		- .800	- .877	+ .773	- 3.48
8	1.000	+ .512		- .918	- .618	+ .662	+ 1.38
9	1.000	- .189		- .195	- .487	+ .263	+ 0.32
10	1.000	- .494		+ .443	- .236	+ .086	+ 2.71
11	1.000	- .564		+ .605	- .069	+ .022	- 0.73
12	1.000	- .563		+ .603	+ .075	- .025	+ 0.23
13	1.000	- .445		+ .331	+ .300	- .117	- 7.45
14	1.000	- .266		- .048	+ .445	- .219	- 7.05
15	1.000		- .803z	+1.255	- .909	+1.224	- 0.85
16	1.000		-1.156	+ .330	- .672	+1.159	- 2.64
17	1.000		-1.383	- .713	- .298	+ .592	- 1.79
18	1.000		-1.403	- .828	+ .223	- .450	+ 8.35
19	1.000		-1.067	+ .645	+ .756	-1.226	+ 4.17
20	1.000		- .798	+1.264	+ .911	-1.222	+17.54
21	1.000		- .512	+1.451	+ .977	-1.047	+22.66
22	1.000		+ .570	- .980	- .021	+ .007	+ 3.70

where $x = d\gamma$
 $y = dK_1$
 $z = dK_2$
 $u = 100 de$
 $v = 100 d\omega$
 $w = \frac{100 \mu}{(1-e^2)^{\frac{3}{2}}} dT$



Radial Velocity Curve of H.R. 6169.

Dominion Astrophysical Observatory,
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ORBIT OF THE SPECTROSCOPIC BINARY H.R. 8800.

BY REYNOLD K. YOUNG

The star H.R. 8800 (R.A. (1900) $23^{\text{h}} 02.7^{\text{m}}$, $\delta = +45^{\circ} 33'$) was discovered to be a spectroscopic binary by the writer in 1918 from five one-prism plates taken with the 72-inch reflector. These plates indicated that the H and K lines of calcium did not oscillate with the other lines and an orbit was undertaken chiefly on this account. The spectrum is approximately B3 type. All the lines including H and K are rather diffuse and wide though the latter lines are better than the others. The spectrum is very similar to that of H.R. 8427 whose orbit has just recently been finished.

The orbit is based on 27 single-prism plates listed in the table of observations. These plates are taken in three years and hence it was necessary to include the period in the least squares solution. The approximate period was selected as 3.337 days. With the aid of this period the observations were grouped into 16 normal places as given below. This procedure is not theoretically sound as the observations which go to make up a normal have different values for the differential coefficient determining the period but practically, if a normal place includes only a few revolutions, the solution is almost as rigid as if each place is treated separately and the labour is greatly reduced.

OBSERVATIONS OF H.R. 8800

Plate	Date	Julian Day	Velocity	No. of Lines	Wt.	Phase from T	O-C	K Line
1918								
370	July 16	2,421,791.968	- 39.9	3	1	1.114	- 6.0	-16.8
421	" 30	1,805.950	+ 25.5	3	1	1.747	- 5.1	.....
566	Sept. 5	1,842.898	+ 49.2	3	1	1.986	+ 2.0	.....
885	Nov. 20	1,918.644	- 57.9	6	1	0.976	- 6.9	+ 0.4
1129	Dec. 23	1,951.567	-128.6	3	$\frac{1}{2}$	0.527	-24.2	- 4.8
1919								
2319	July 8	2,148.957	- 43.8	7	1	1.022	+ 1.2	- 4.5
2333	" 9	2,149.945	+ 40.6	3	1	2.010	- 8.4	-18.0
2360	" 13	2,153.954	+ 68.6	3	1	2.682	+18.2	- 0.1
2395	" 15	2,155.961	- 15.5	5	1	1.352	- 8.7	+ 8.7
2445	" 19	2,159.969	+ 56.8	4	1	2.023	+ 6.8	-23.7
2464	" 20	2,160.966	- 7.2	4	1	3.020	- 6.4	- 6.9
2521	" 23	2,163.963	.....	.....	0	2.679	.....	.....
2607	Aug. 6	2,177.957	- 85.6	5	1	3.325	-10.1	-16.8
2620	" 7	2,178.924	- 55.2	4	1	0.954	- 2.2	.....
2655	" 10	2,181.911	- 82.6	6	1	0.604	+13.4	-14.2
2696	" 14	2,185.955	- 0.5	4	1	1.311	+10.7	.....
2753	" 19	2,190.772	+ 45.8	5	1	2.791	+ 5.8	-17.1
2763	" 19	2,190.903	+ 14.0	6	1	2.922	- 5.6	- 8.5
2767	" 19	2,190.969	+ 14.6	3	1	2.988	+ 8.6	.....
2782	" 20	2,191.919	- 96.1	3	1	0.601	+ 0.7	- 3.7
2778	" 20	2,191.822	- 97.1	3	1	0.504	+ 8.9	.....
2793	" 21	2,192.902	+ 31.3	1	$\frac{1}{2}$	1.584	+14.6	.....
2810	" 22	2,193.890	+ 50.4	3	1	2.572	- 4.7	+ 0.4
1920								
4631	July 14	2,520.954	+ 49.0	7	1	2.590	- 7.8	.....
4650	" 18	2,524.963	- 58.7	4	1	3.262	+ 1.3	- 6.7
4702	" 25	2,531.906	-114.1	5	1	0.193	- 2.4	-20.7
4703	" 25	2,531.927	-115.5	6	1	0.214	- 5.5	-11.8
4728	" 27	2,533.908	.....	.....	0	2.195	.....	.....
4739	" 28	2,534.932	- 24.8	3	$\frac{1}{2}$	3.219	+24.2	.....

NORMAL PLACES

	Mean Epoch Julian Date	Phase from Final T	Velocity	No. of Observations	Wt.	O-C Prelim.	O-C Final.	pv^2 Prelim.	pv^2 Final.
1	2,421,791.968.....	1.114	- 39.9	1	$\frac{1}{2}$	- 1.4	- 6.0	1	18
2	1,805.950.....	1.747	+ 25.5	1	$\frac{1}{2}$	- 6.6	- 5.1	22	13
3	1,842.898.....	1.986	+ 49.2	1	$\frac{1}{2}$	- 1.7	+ 2.0	2	2
4	1,918.644.....	0.976	- 57.9	1	$\frac{1}{2}$	- 3.1	- 6.4	5	20
5	1,951.567.....	0.527	-128.6	1	$\frac{1}{4}$	-22.4	-24.2	125	146
6	2,191.888.....	0.570	- 91.9	3	$1\frac{1}{2}$	+ 9.3	+ 8.5	131	107
7	2,178.957.....	0.987	- 49.5	2	1	+ 2.0	+ 0.1	4	0
8	2,185.975.....	1.331	- 8.0	2	1	+ 1.0	+ 0.9	1	1
9	2,192.902.....	1.584	+ 31.3	1	$\frac{1}{4}$	+12.5	+14.6	39	53
10	2,159.962.....	2.016	+ 48.7	2	1	- 5.3	- 0.2	28	0
11	2,193.999.....	2.681	+ 54.9	3	$1\frac{1}{2}$	+ 6.2	+ 4.6	57	31
12	2,190.957.....	2.976	+ 7.2	3	$1\frac{1}{2}$	+ 8.0	- 1.9	84	6
13	2,177.957.....	3.325	- 85.6	1	$\frac{1}{2}$	- 2.5	-10.1	3	51
14	2,520.954.....	2.590	+ 49.0	1	$\frac{1}{2}$	- 6.3	- 6.1	20	18
15	2,531.916.....	0.203	-114.8	2	1	- 1.7	- 4.6	3	22
16	2,534.960.....	3.234	- 47.4	2	$\frac{3}{4}$	+23.9	+ 5.9	429	28

Σ 954 516

The following preliminary elements were selected as a basis for the least squares solution

$$\begin{aligned}
 P &= 3.337 \text{ days} \\
 e &= 0.20 \\
 \omega &= 120^\circ \\
 T &= \text{J.D. } 2,422,151.200 \\
 K &= 90 \text{ km.} \\
 \gamma &= -16.2 \text{ km.}
 \end{aligned}$$

The residuals left in the normal places from these elements are given in the table under the heading, O-C preliminary. Observation equations were next formed and the solution gone through in the usual way. The changes in the elements are rather larger than usual and the residuals computed from the ephemeris differed in some cases from that computed from the observation equations. The solution resulted in a lowering of Σpv^2 from 954 to 516 so that a second solution would probably improve the residuals still further. As will be seen from the probable errors of the elements the changes of the present solution are of the same order as these and as the next solution would probably result in much smaller changes, they may be taken as negligible. The several steps in the solution are recorded.

OBSERVATION EQUATIONS

1	1.000x	-1.076y	-0.389z	-0.854u	+0.278v	-0.212w	+ 1.72 = 0
2	1.000	-1.001	+0.262	+0.410	-0.448	-0.180	+22.35
3	1.000	-0.945	+0.362	+0.609	-0.526	+0.052	- 9.32
4	1.000	-0.430	+0.771	+0.851	-0.714	-0.332	+ 3.14
5	1.000	-0.392	+0.783	+0.857	-0.713	+0.040	- 1.95
6	1.000	-0.245	+0.816	+0.683	-0.704	-0.506	+ 1.35
7	1.000	+0.082	+0.810	+0.120	-0.648	+0.045	- 0.95
8	1.000	+0.388	+0.699	-0.478	-0.558	+0.047	-12.53
9	1.000	+0.536	+0.598	-0.740	-0.497	-0.343	+ 6.59
10	1.000	+0.746	+0.361	-0.972	-0.362	-0.223	+ 1.70
11	1.000	+0.780	+0.302	-0.975	-0.327	+0.006	+ 5.29
12	1.000	+0.794	-0.621	+0.426	+0.438	-0.324	+ 6.26
13	1.000	+0.721	-0.744	+0.695	+0.590	-0.051	- 6.21
14	1.000	+0.172	-1.136	+1.037	+1.250	-0.100	- 7.96
15	1.000	-0.612	-1.032	-0.529	+1.236	-0.949	-23.92
16	1.000	-0.744	-0.938	-0.806	+1.096	-0.059	+ 2.48

where

$$x = d\gamma$$

$$y = dK$$

$$z = Kd\omega$$

$$u = Kde$$

$$v = \frac{K\mu}{(1-e^2)^{\frac{3}{2}}} dT$$

$$w = \frac{K d\mu}{(1-e^2)^{\frac{3}{2}}} \times 500$$

NORMAL EQUATIONS

$$\begin{array}{r}
 12.750x - 0.970y - 0.811z + 1.967u + 0.865v - 1.910w - 35.850 = 0 \\
 + 5.796 - 0.590 - 0.278 + 0.609 + 0.402 + 14.693 \\
 + 6.920 - 0.597 - 6.872 + 0.789 + 32.785 \\
 + 7.390 + 0.469 + 0.282 - 23.637 \\
 + 7.056 - 0.942 - 36.055 \\
 + 1.077 + 13.089
 \end{array}$$

$$x = +1.07$$

$$y = -2.30$$

$$z = +8.91$$

$$u = +2.93$$

$$v = +12.94$$

$$w = -5.37$$

$$d\gamma = +1.07$$

$$dK = -2.30$$

$$d\omega = +5^{\circ}.67$$

$$de = +.0326$$

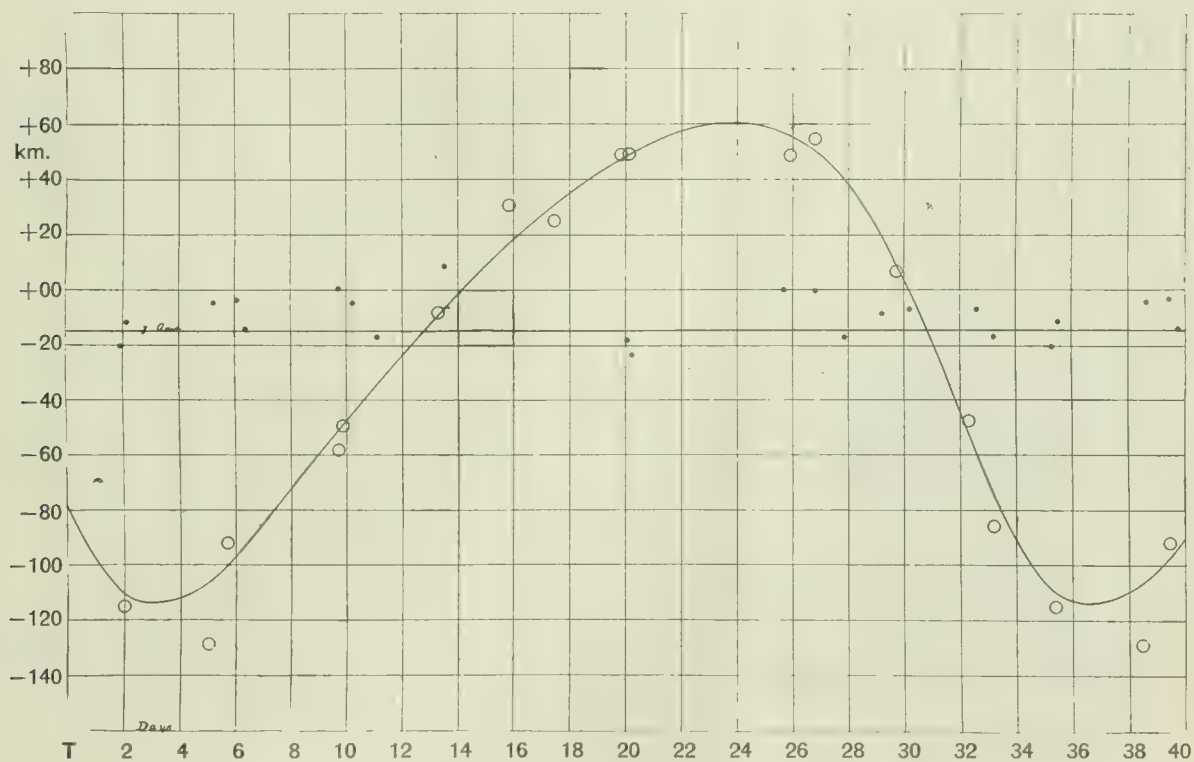
$$dT = +.0718 \text{ day}$$

$$dP = +.00020 \text{ day}$$

The final elements with their probable errors are

P = period	= 3.3372 days	± 0.00023
e = eccentricity	= .2326	± 0.022
ω longitude of periastron	= $125^{\circ}.67$	$\pm 7^{\circ}.08$
K = semi-amplitude	= 87.70 km.	± 2.68
T = periastron passage	= J.D. 2,422,151.272	± 0.0623
γ = velocity of system	= -15.13 km.	± 1.79
V = velocity of Calcium	= -9.1 km.	± 1.39
$a \sin i = 3,910,000$ km.		

$$\frac{m_1^3 \sin^3 i}{(m+m_1)^2} = 0.215 \odot$$



Radial Velocity Curve of H.R. 8800

Open circles represent normal places. Small circles represent velocities from H and K lines.

Dominion Astrophysical Observatory,
Victoria, B.C.

August 26, 1920.

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THE ORBITS OF THE SPECTROSCOPIC COMPONENTS OF BOSS 4602

BY S. L. BOOTHROYD

This star ($\alpha = 18^h 07.5^m$, $\delta = +79^\circ 59'$, photographic magnitude 6.6, type F5) is one of the first twelve binaries discovered at the Dominion Astrophysical Observatory at Victoria, B.C., the announcement of which appeared first in the "Journal of the Royal Astronomical Society of Canada" for November 1918.

Dr. J. S. Plaskett secured five plates of the star, in the programme of radial velocity determinations, between June 19 and July 21, 1918. His measures of these five spectrograms revealed the binary character of the star. Between July 1, 1919, and September 18, 1919, 28 plates were secured. All of these, as well as those secured by Dr. Plaskett in 1918, were measured on the Hartmann Comparator, using a sky or a Mars standard. From the measures of the first 14 or 15 of the 1919 plates together with Dr. Plaskett's measures of 1918 the period was found to be very close to 10.5 days. This made it possible to get the remaining plates well distributed along the velocity curve. The velocities did not, however, agree well with any elliptic curve, although those at nearly the same phase showed as reasonable agreement as was to be expected. Measures of plate number 2923 on the Hartmann Comparator proved an exception to this rule and a closer examination of the plate revealed close companion lines to at least ten of the lines. A re-examination of all of the previous plates, including those secured by Dr. Plaskett in 1918, showed that on seven of these plates from four to ten lines showed double. Since the lines of the two components are just separable, for one-prism dispersion, and

besides this only those lines which are most intense show at all for the secondary component, it is easy to see why they were overlooked on the few plates on which from two to ten show at all. The table of observations lists only those plates which show double lines since these were the only plates used in the final determination of the orbits. The second column gives the initial of the person securing the spectrogram. All of the measures were made by the author except that the lines of the secondary component on plates 2484 and 2937 were also measured by Mr. Harper, the mean of his measures and the author's being used.

The writer had to leave Victoria on September 18, 1919, to resume his duties at the University of Washington and bad weather prevented securing more plates, at phases which would show the double lines, before October 15, and after that it was inadvisable to attempt to get any more plates in 1919, owing to the unfavourable position of the star for observation. However, in April 1920, Mr. Harper and Dr. Plaskett kindly secured three more plates at such phases as to show the lines double. Again in August 1920, four more plates were again secured at such phases as to show some of the lines double. Sixteen plates in all were therefore secured which show double lines and the orbit is based entirely on the measures of these sixteen plates. The remaining twenty-six plates were measured on either the Hartmann Comparator or the Gaertner measuring machine or on both, but none of these measures were used in the final computations for the orbital elements.

The lines of the secondary component are quite faint whereas those of the principal component are rather diffuse and much more numerous. The probable error of a plate for the principal component is ± 2.36 and for the secondary ± 4.65 km. per second. The mass of the secondary component is 0.903 times that of the principal component.

In the following table of observations the phases are reckoned from the final value of periastron passage using the corrected period 10.5217 days.

OBSERVATIONS OF BOSS 4602

Plate Number	Ob-server	Date	Julian Date	Phase	Component 1			Component 2		
					Vel.	Lines	O-C	Vel.	Lines	O-C
1918										
217	P	June 22	2,421,767.804	3.1559	+38.3	6	+0.4	-34.7	6	+ 1.4
1919										
2238	P	July 1	2,141.798	8.8904	-43.9	9	+1.4	+61.9	9	+ 5.2
2484	B	" 22	2,162.729	8.7780	-42.3	9	+1.7	+65.2	8	+ 9.9
2510	Y	" 23	2,163.769	9.8180	-41.7	6	-1.6	+58.0	4	+ 7.1
2595	Y	Aug. 6	2,177.716	2.7216	+47.0	4	+5.0	-40.9	5	- 0.2
2714	H	" 15	2,186.796	1.2739	+42.7	2	+2.0	-39.9	2	- 0.7
2798	Y	" 22	2,193.671	8.1549	-37.2	7	-1.2	+45.2	5	- 1.1
2923	H	Sept. 12	2,214.641	8.0815	-39.4	10	-4.6	+39.6	9	- 5.4
2937	Y	" 13	2,215.634	9.0745	-44.6	5	+1.6	+57.1	6	- 0.7
1920										
4057	H	April 9	2,424.993	7.9995	-33.7	6	-0.2	+41.4	5	- 2.2
4148	H	" 23	2,438.952	0.9151	+31.1	7	-1.0	-33.8	7	- 4.2
4190	H	" 30	2,445.958	7.9211	-37.2	5	-4.9	+32.1	3	-10.1
4790	P	Aug. 5	2,542.749	10.0161	-31.8	7	+2.4	+54.5	7	+10.1
4802	P	" 7	2,544.679	1.4251	+40.6	6	-2.3	-43.9	4	-22.2
4814	Y	" 8	2,545.704	2.4501	+42.2	10	-1.9	-42.8	11	+ 0.2
4826	B	" 9	2,546.696	3.4421	+39.2	4	+4.4	-21.3	5	+11.3

From the preliminary elements, given later, observation equations were built up according to the notation of Lehman-Filhés, modified to suit the case of double spectra,* and a least squares solution effected. Since the observations extended over parts of three seasons, the period was also included in the solution. This necessitated treating all the observations separately.

By making the following transformation a set of 32 observation equations involving the seven unknowns γ , K_1 , K_2 , e , ω , P , and T were built up. The weights are given in the last column.

$$\begin{aligned}
 x &= \delta\gamma \\
 y &= \delta K_1 \\
 z &= \delta K_2 \\
 t &= 50 \delta e \\
 u &= [2.81500] \delta P \\
 v &= 50 \delta \omega \\
 w &= [1.53628] \delta T
 \end{aligned}$$

*Dominion Observatory Publications, Vol. 1, page 327.

OBSERVATION EQUATIONS FOR BOSS 4602

1	1.000x	+0.677y	0.000z	-0.915t	+0.811u	-0.410v	+0.420w	-4.600	=0	4
2	1.000	-0.996	0.000	+0.170	+0.005	+0.203	+0.075	-1.000		5
3	1.000	-0.987	0.000	+0.321	-0.006	+0.130	+0.137	-2.200		5
4	1.000	-0.796	0.000	-1.085	+0.038	+0.851	-0.794	+6.200		4
5	1.000	+0.859	0.000	-0.838	-0.041	-0.199	+0.344	-4.800		2
6	1.000	+0.920	0.000	+0.790	+0.075	+0.650	-0.461	+2.400		3
7	1.000	-0.869	0.000	+0.822	-0.067	-0.184	+0.337	-1.800		4
8	1.000	-0.848	0.000	+0.854	-0.107	-0.216	+0.352	+1.400		5
9	1.000	-1.000	0.000	-0.033	+0.005	+0.297	-0.015	-0.500		4
10	1.000	-0.798	0.000	+0.904	-0.515	-0.285	+0.381	-1.900		4
11	1.000	+0.649	0.000	+1.136	+1.535	+0.996	-1.078	+1.300		4
12	1.000	-0.773	0.000	+0.917	-0.572	-0.315	+0.391	+2.800		4
13	1.000	-0.793	0.000	-1.089	+1.556	+0.854	-0.801	-3.600		4
14	1.000	+0.909	0.000	+0.831	+0.967	+0.673	-0.495	+4.000		4
15	1.000	+0.956	0.000	-0.552	-0.448	+0.008	+0.228	+4.600		5
16	1.000	+0.708	0.000	-0.923	-0.809	-0.382	+0.412	-4.000		3
17	1.000	0.000	-0.677	+0.974	-0.862	+0.436	-0.447	+2.700		2
18	1.000	0.000	+0.996	-0.181	-0.005	-0.216	-0.080	-10.200		1
19	1.000	0.000	+0.987	-0.342	+0.006	-0.138	-0.146	-14.000		1
20	1.000	0.000	+0.796	+1.155	-0.041	-0.905	+0.845	-16.300		1
21	1.000	0.000	-0.859	+0.892	+0.043	+0.212	-0.366	-0.200		2
22	1.000	0.000	-0.920	-0.840	-0.080	-0.692	+0.490	-4.200		1
23	1.000	0.000	+0.869	-0.875	+0.071	+0.196	-0.359	+0.100		2
24	1.000	0.000	+0.848	-0.909	+0.113	+0.230	-0.375	+4.700		2
25	1.000	0.000	+1.000	+0.035	-0.005	-0.316	+0.016	-5.200		1
26	1.000	0.000	+0.798	-0.962	+0.055	+0.303	-0.405	+0.400		2
27	1.000	0.000	-0.649	-1.209	-1.633	-1.060	+1.147	+3.200		2
28	1.000	0.000	+0.773	-0.976	+0.608	+0.335	-0.416	+8.400		1
29	1.000	0.000	+0.793	+1.159	-1.656	-0.909	+0.852	-13.000		1
30	1.000	0.000	-0.909	-0.884	-1.029	-0.716	+0.527	+0.300		2
31	1.000	0.000	-0.956	+0.587	+0.476	-0.008	-0.243	-3.100		2
32	1.000	0.000	-0.708	+0.982	+0.860	+0.406	-0.438	-12.200		1

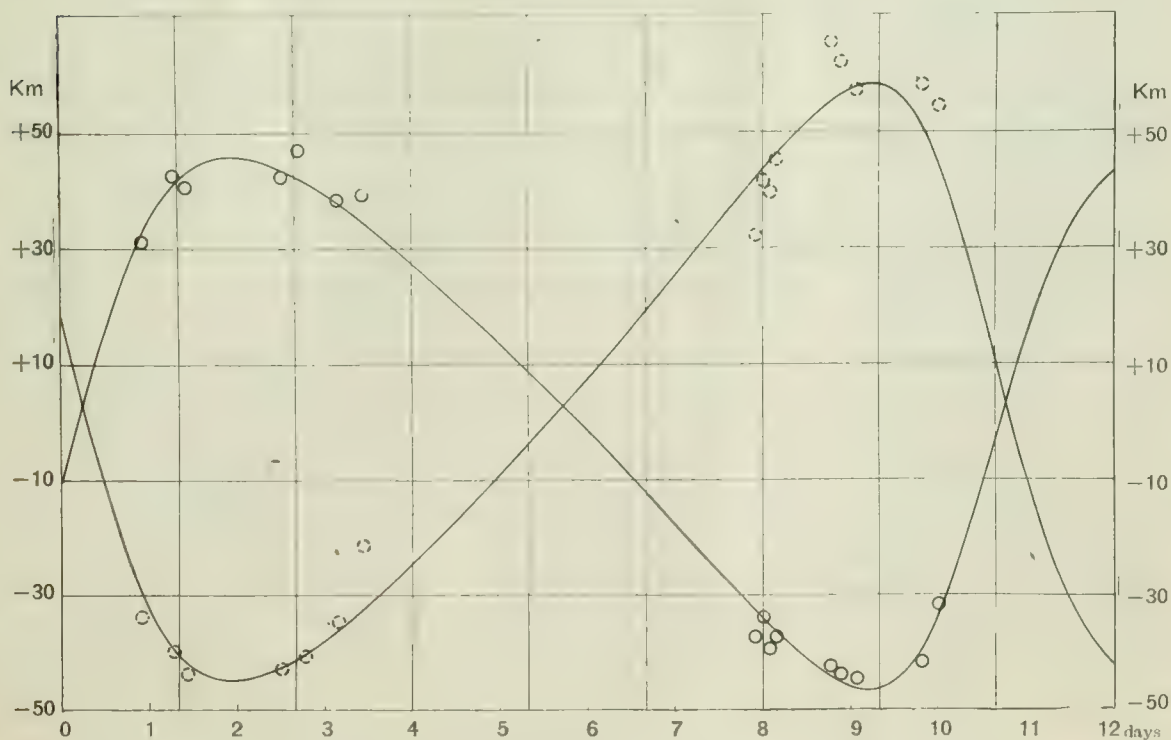
NORMAL EQUATIONS

$$\begin{aligned}
 22.000x - 3.487y + 0.162z + 1.017t + 1.033u + 1.925v - 0.510w - 10.825 &= 0 \\
 +11.837 &+ 0.000 &- 1.988 &+ 1.249 &- 0.056 &- 0.797 &+ 6.143 \\
 &+ 1.276 &- 1.180 &+ 0.784 &+ 0.363 &- 0.494 &- 6.692 \\
 &&+ 15.220 &+ 0.500 &+ 0.675 &- 0.177 &- 6.146 \\
 &&&+ 11.051 &+ 5.458 &- 5.625 &- 3.955 \\
 &&&&+ 5.613 &- 5.279 &+ 17.423 \\
 &&&&&+ 5.590 &- 13.837
 \end{aligned}$$

The solution of these equations gave corrections to the preliminary elements, as given in the following table. One solution was deemed to be all that was warranted from the data at hand, as judged by the fair agreement of the final ephemeris residuals with those obtained by substitution in the observation equations. The sum of the squares of the residuals for the observed places was reduced from 1757 to 1082, or about 38 per cent.

TABLE OF ELEMENTS

Element		Preliminary	Final
Period.....	P	10.527 days.....	10.5217 ± 0.0018 days
Eccentricity.....	e	0.30.....	0.314 ± 0.014
Longitude of apse.....	ω_1	270°.....	256°.76 $\pm 4^\circ.38$
Longitude of apse.....	ω_2	90°.....	76°.76 $\pm 4^\circ.38$
Velocity of system.....	γ	+1.88 km. per sec..	+2.93 ± 0.62 km. per sec.
Semi-amplitude primary.....	K_1	47 km.....	46.16 ± 0.83 km.
Semi-amplitude secondary.....	K_2	50 km.....	51.50 ± 1.32 km.
Periastron passage.....	T	J.D. 2,421,764.592.....	J.D. 2,421,764.6481 ± 0.1112
Semi-major axis.....	$a_1 \sin i$		6,341,000 km.
Semi-major axis.....	$a_2 \sin i$		7,074,000 km.
Mass primary.....	$m_1 \sin^3 i$		0.457 \odot
Mass secondary.....	$m_2 \sin^3 i$		0.413 \odot



Radial Velocity Curves of Boss 4602 Showing Individual Observations.

The graph shown represents the velocity curves using the final elements. Individual observations are plotted. An interesting problem, reserved for the future, will be to re-determine these orbits from plates obtained with higher dispersion.

I wish here to express my appreciation of the kindness shown me by Dr. Plaskett and all the members of his staff at the Dominion Astrophysical Observatory at Victoria during my stay at the Observatory for twelve weeks of the summer of 1919 and six weeks of the summer of 1920. Every possible facility and assistance were extended to aid me in the prosecution of the work on Boss 4602 and on other spectroscopic binaries on which I am working, the results of which work will appear as soon as completed.

University of Washington,
Seattle, Wash.

October 1 1920.



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THE SPECTROSCOPIC ORBIT AND DIMENSIONS OF Z VULPECULÆ

BY J. S. FLASKETT

The eclipsing variable Z Vulpeculæ, R.A. $19^h 17.5^m$, Dec. $+ 25^\circ 23'$ (1900), mag. 7.1, spectral type B3, has had its photometric orbit determined by Shapley, being placed by him in the second grade of the orbits determined, so that the photometric results are fairly reliable. This is the seventh eclipsing variable to have its spectroscopic orbit determined here and was placed under observation on April 22, 1920, the last plate being obtained on Nov. 7. In this interval 18 spectra were secured, all being used in the determination of the orbit.

The spectra are of type B3 and, as usual in eclipsing variables, the lines are diffuse and difficult to accurately set upon under the microscope. Although the brighter star gives three-fourths of the light of the system, the spectrum of the fainter component has been measured on twelve of the plates giving results in fair inter-agreement among themselves and there can hence be no doubt of the reality of its presence. The spectrum of the fainter star is practically the same type B3 as the brighter with equally diffuse lines, and as they are relatively faint the accuracy of measurement is correspondingly less, as indicated by the probable error of a single plate as determined from the final orbit which is ± 6.0 km. per second for the bright component and ± 10.1 km. for the faint. The lines measured in each component consist of the hydrogen lines $H\gamma$ and $H\delta$, helium 4472, 4388, 4144, 4026, magnesium 4481, and carbon 4267. In order to reduce some of the accidental errors of measurement practically all the spectra were twice measured, some three times, the mean value of the individual measures being used.

The following table contains observational and other data of Z Vulpeculæ. The first three columns contain the plate number, the day and the Julian date of the observations. The fourth column gives the phase computed from the initial photometric phase used by Shapley* $2,419,679.925 + 2.45492$ days. The fifth and sixth columns contain the mean measured velocities of primary and secondary component while the seventh and eighth columns give the residuals in the sense observed minus computed from the corrected orbit.

*Contributions from Princeton Observatory, No. 3, p. 17.

OBSERVATIONS OF Z VULPECULÆ

Plate Number	Date	Julian Date	Phase	Velocities		Residuals	
				Principal	Secondary	Principal	Secondary
	1920						
4128	April 22.....	2,422,437.993	1.443	+ 21.7		-10.8	
4292	May 13.....	2,458.938	0.294	- 89.4		+10.1	
4432	June 18.....	2,494.936	1.923	+ 83.6	-213.8	+ 3.8	+11.8
4529	July 1.....	2,507.872	0.129	- 63.3		-20.2	
4636	" 16.....	2,522.835	0.363	- 83.3		+ 6.8	
4667	" 22.....	2,528.917	1.535	+ 54.5	-161.9	+ 3.7	- 2.9
4729	" 27.....	2,533.937	1.645	+ 66.1	-212.7	- 1.5	-14.7
4756	Aug. 1.....	2,538.869	1.667	+ 61.2	-195.0	- 9.0	+ 9.5
4789	" 5.....	2,542.717	0.605	-119.4	+206.3	- 8.1	+ 8.0
4795	" 5.....	2,542.903	0.791	-114.4	+172.6	-11.3	- 7.3
4861	" 11.....	2,548.794	1.772	+ 85.9	-199.7	+ 6.8	+24.3
4874	" 12.....	2,549.895	0.419	- 92.4	+202.6	+ 5.7	+33.8
5008	Sep. 2.....	2,570.712	1.596	+ 70.4	-170.6	+ 9.4	+11.9
5049	" 6.....	2,574.735	0.709	-105.2	+192.2	+ 4.3	+ 1.0
5070	" 16.....	2,584.729	0.884	- 79.5		+12.2	
5094	" 27.....	2,595.787	2.122	+ 50.6	-186.0	- 9.0	- 5.2
5255	Oct. 25.....	2,623.633	0.509	-103.3	+197.2	+ 1.6	+ 8.7
5423	Nov. 7.....	2,636.626	1.227	- 18.8		- 0.2	

These observations are not well distributed over the period being crowded together at the maximum velocities and rather sparsely distributed near eclipses. This was due to the length of period nearly two and a half days and to cloudy weather at critical epochs. Nevertheless, there are sufficient observations to determine the orbit nearly as well as possible and it did not seem worth while to carry the work into another season. The observations were accordingly grouped into normal places, thirteen for the principal and eight for the secondary component respectively. The number of plates in each group is indicated by the weights assigned, each primary spectrum being given a weight of one and each secondary spectrum a weight of one-half. The difference of phase in any group does not exceed 0.09 days.

NORMAL PLACES OF Z VULPECULÆ

Weights		Phase from Minimum	Mean Velocities		Residuals (Prel.)		Residuals (Final)	
Prim.	Sec.		Primary	Secondary	Primary	Secondary	Primary	Secondary
1		0.129	- 63.3		-20.18		-20.18	
2		0.328	- 86.35		- 2.82		- 1.75	
2	1	0.464	- 98.85	+199.9	+ 2.18	+15.29	+ 4.28	+19.76
1	$\frac{1}{2}$	0.605	-119.4	+206.3	-11.43	+ 6.36	- 8.12	+ 8.00
2	1	0.750	-109.8	+182.4	- 7.58	- 4.84	- 3.27	- 5.84
1		0.884	- 79.5		+ 6.44		+12.21	
1		1.227	- 18.8		- 6.68		- 0.25	
1		1.443	+ 21.7		-16.61		-10.83	
1	$\frac{1}{2}$	1.535	+ 54.5	-161.9	- 1.50	+ 0.26	+ 3.74	- 2.91
3	$\frac{1}{2}$	1.636	+ 65.9	-192.8	- 5.17	+ 2.64	- 0.60	+ 3.36
1	$\frac{1}{2}$	1.772	+ 85.9	-199.7	+ 2.41	+20.97	+ 6.79	+24.34
1	$\frac{1}{2}$	1.923	+ 83.6	-213.8	+ 1.70	+ 5.56	+ 3.79	+11.77
1	$\frac{1}{2}$	2.122	+ 50.6	-186.0	- 9.65	-14.45	- 9.00	- 5.25

When these normal places were plotted on cross section paper it was evident that a circular orbit would satisfy the observations as well as could be expected, and although the photometric orbit indicates the presence of a small eccentricity, $e \cos \omega = 0.013$, the spectroscopic observations are of insufficient accuracy, owing to the diffuse lines, to determine its magnitude which is probably not over 0.02. Preliminary elements obtained graphically were taken as follows. Velocity of system -12 km. per second and semi-amplitude of primary and secondary as 96 and 212 km. per second respectively. Although the observations seemed to indicate that the spectroscopic phase was slightly earlier than the photometric, the latter was accepted for the preliminary orbit.

With these elements an ephemeris was computed and observation equations formed introducing corrections for the velocity of the system, for the semi-amplitudes of primary and secondary and for the phase. The coefficients of the phase were divided by 100 in order to make the magnitudes of all more nearly equal. The resulting normal equations

$$\begin{array}{rcll} 35.50\delta\gamma & - & .8086\delta K_1 & - .6857\delta K_2 + .8058\delta\phi = -113.85 \\ & + & 20.8976\delta K_1 & + 6.002\delta\phi = -11.44 \\ & & + 4.4263\delta K_2 & + 2.1223\delta\phi = +2.23 \\ & & & + 13.2148\delta\phi = -43.70 \end{array}$$

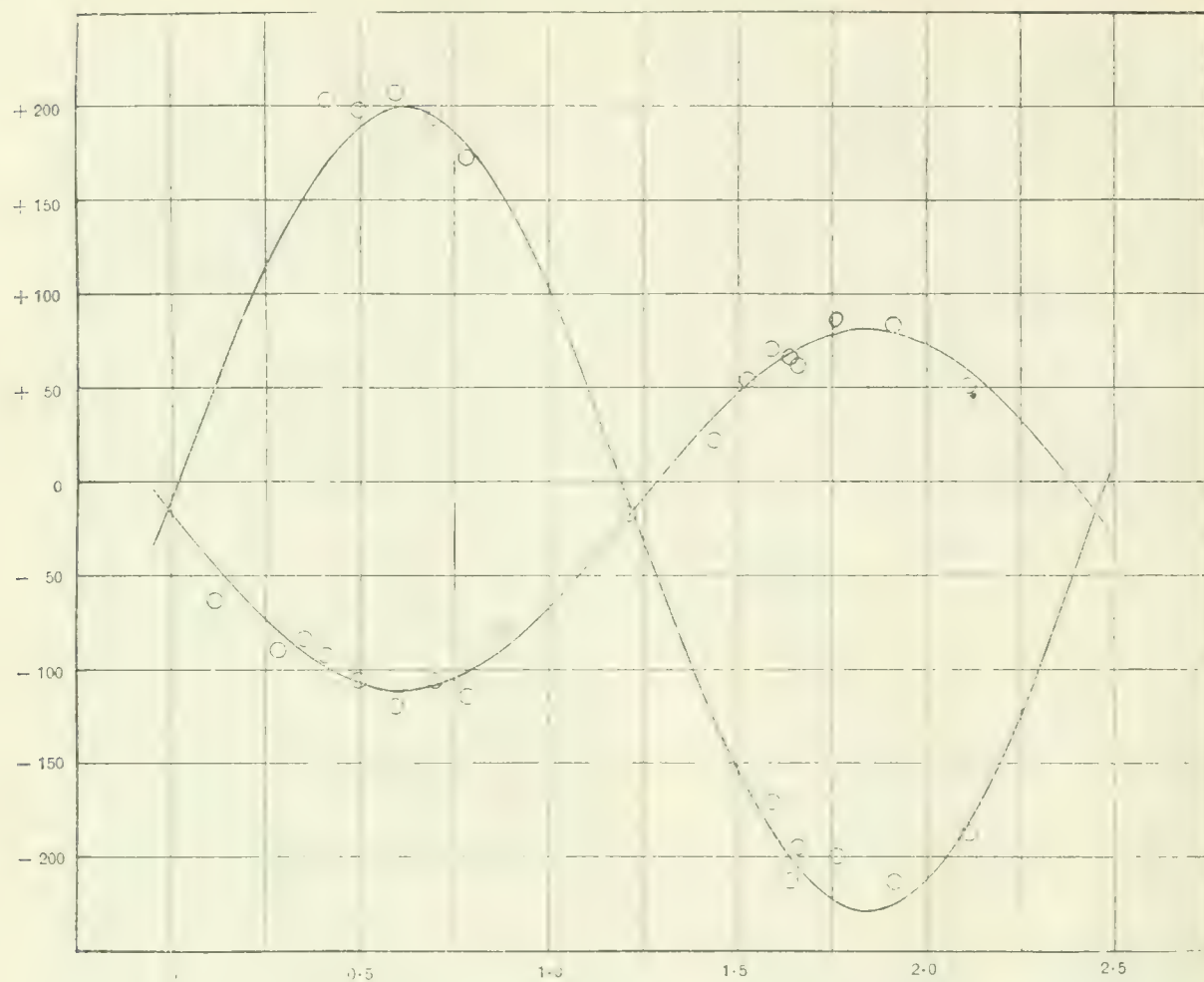
when solved gave the following values of the corrections and final values of the element

$$\begin{array}{ll} \delta\gamma & = -3.08 & \gamma & = -15.08 \pm 1.1 \text{ km. per sec.} \\ \delta K_1 & = +0.35 & K_1 & = 96.35 \pm 1.4 \text{ km. per sec.} \\ \delta K_2 & = +1.74 & K_2 & = 213.74 \pm 5.6 \text{ km. per sec.} \\ \delta\phi & = -0.03554 = -2^\circ.04 & T & = -0.014 \pm 0.008 \text{ days} \end{array}$$

The probable error of a normal place of unit weight is ± 6.3 km. per second, of the measure of the primary spectrum on a plate is ± 6.0 and of the secondary ± 10.1 km. per second. $\Sigma p v^2$ was reduced by the solution about 25 per cent for the primary spectrum and increased about 15 per cent for the secondary. The displacement of the spectroscopic phase, about 20 minutes earlier than the photometric, is only slightly greater than the probable error and considering the character and distribution of the observations, is not entitled to much weight. So far as eccentricity of the orbit is concerned, the accompanying velocity curve on which the separate observations are plotted as circles, shows that it must be exceedingly small and is quite indeterminate from the observations.

Shapley obtains two solutions of the photometric orbit*, uniform and darkened, and using his values of the inclination and the relative radii of the two components we obtain the following absolute dimensions of the system of Z Vulpeculæ.

*Contributions from Princeton Observatory, No. 3, p. 86.



Velocity Curve and Dimensions of Z Vulpeculæ.

			Uniform	Darkened
Separation of two stars	a	—	15.06 \odot	15.05 \odot
Radius bright star	r_1	=	3.78	4.23
Radius faint star	r_2	=	4.73	4.46
Mass bright star	m_1	=	5.25	5.24
Mass faint star	m_2	=	2.37	2.36
Density bright star	ρ_1	=	.135	.085
Density faint star	ρ_2	=	.031	.033

If we assume with Shapley that the surface intensity of a B3 star as compared with the sun is -2.7 magnitudes the absolute magnitude of the brighter component of Z Vulpeculæ is about -0.9 ; its apparent magnitude is 7.4 and hence its parallax is $0''.0022$. The absolute dimensions of the system as compared with the sun are graphically shown in the figure, but no attempt is made to show the elliptic form of the components.

Dominion Astrophysical Observatory,

Victoria, B.C.,

Nov. 1920.



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THE ORBIT OF THE SPECTROSCOPIC BINARY BOSS 5070

BY W. E. HARPER

This star ($1900\ \alpha = 19^{\text{h}}\ 47.2^{\text{m}}, \delta = +40^{\circ}\ 20'$, visual magnitude 5.62, type B3) was announced as a spectroscopic binary by Adams in the Publications of the *Astronomical Society of the Pacific*, Volume 26, page 261. The data of his three plates, communicated to the writer while at Ottawa, appear in the table of observations. They have served to determine the period much more accurately than could be done without them but have not otherwise been made use of. Seven plates were also made by the writer at Ottawa, as given in *Publications of the Dominion Observatory*, Volume 4, page 374, but the star was dropped from our list at that time as it was understood the Allegheny Observatory had about completed the investigation of its orbit. As no orbit has yet appeared and as the Ottawa observations indicated a possible period it was decided to make more observations and complete the work.

The Ottawa observations indicated that the K-line of calcium did not share in the large range of the hydrogen and helium lines and an effort has been made to have the Victoria plates well exposed in that region so as to secure as reliable velocities for it as possible. Nineteen out of the twenty-one plates upon which this investigation is based show K as a fairly sharp line whose velocity may be considered constant. On a couple of plates it has a peculiar appearance as if winged to the red side but it seems preferable to consider these as defects of the film and treat the line as constant in character and with a velocity of -17.4 ± 1.0 km. per sec. This result is based on the wave length 3933.825 for the calcium line. Attention may be drawn to the fact that this velocity is about 11 km. more negative than the velocity of the system and also that if allowance be made for the motion of the solar system through space its velocity will be approximately zero.

Besides the usual hydrogen and helium series whose lines, though approximately 3 angstroms in width, are fairly well measurable there are two rather poor silicon lines $\lambda 4552$ and $\lambda 4567$. The magnesium line at $\lambda 4481$ and the carbon at $\lambda 4267$ are faint but sometimes measurable so that in all from five to eleven lines are measured on each plate as indicated in the table of observations. The phases are reckoned from the value of periastron passage finally adopted using the period of 12.427 days which was obtained by connecting up the early Mount Wilson observations with those made here this summer. The Ottawa observations suggested such a value and fit in with the curve though with somewhat more ragged agreement than the present series. Slight differences of wave lengths used in the two cases may account to a small extent for the lack of good agreement. In any case the orbit is based upon the Victoria plates alone, the data for which are given in the following table.

OBSERVATIONS OF BOSS 5070

Plate Number	Date	Julian Date G.M.T.	Phase	Velocity	Lines	Residual O C	K-line	
							Vel.	Wt.
1912								
Mount Wilson	Aug. 29.	2,419,644.848	8.622	+ 80.0		+2.0		
"	Sep. 18.	664.799	3.719	- 53.9		-2.9		
"	Oct. 31.	2,419,707.615	9.254	+ 85.6		+7.0		
1920								
4467	June 25.	2,422,501.894	7.458	+ 67.7	5	+5.7		
4487	" 28.	504.884	10.448	+ 53.8	8	-1.2	- 1.6	1 $\frac{1}{4}$
4575	July 5.	511.892	5.029	- 5.8	7	-0.8	-16.7	1
4598	" 7.	513.841	6.978	+ 48.7	7	-2.7	-23.7	1
4673	" 23.	529.802	10.512	+ 51.3	6	-0.7	- 3.4	1
4883	Aug. 13.	550.848	6.704	+ 43.4	9	-1.6	-13.6	1
4908	" 20.	557.747	1.176	-106.0	8	+2.8	-17.8	1
4926	" 22.	559.684	3.113	- 71.7	11	+0.7	-25.5	$\frac{1}{4}$
4944	" 29.	566.700	10.129	+ 60.7	11	-4.1	-22.8	1
4976	" 31.	568.723	12.152	- 46.5	10	-1.9	-19.2	1 $\frac{1}{2}$
4988	Sep. 1.	569.702	.704	-106.0	10	-7.4	-23.4	1
5024	" 3.	571.755	2.757	- 77.9	11	+6.9	-17.1	1
5050	" 6.	574.756	5.758	+ 14.0	10	-4.5	-18.0	$\frac{1}{4}$
5051	" 6.	574.765	5.767	+ 17.9	9	-0.6		
5082	" 24.	592.801	11.376	+ 14.1	8	+5.5	-29.0	$\frac{1}{4}$
5130	" 29.	597.721	3.869	- 39.1	9	-6.8	-14.2	1 $\frac{1}{4}$
5150	Oct. 8.	606.756	.477	- 91.4	8	-2.2	-14.7	$\frac{1}{4}$
5323	" 29.	627.645	8.939	+ 86.8	11	+8.0	-16.1	$\frac{1}{2}$
5324	" 29.	627.659	8.953	+ 79.6	11	+0.8	-18.1	$\frac{1}{2}$
5448	Nov. 9.	638.605	7.472	+ 65.6	9	+3.6	-17.9	1
5496	" 19.	2,422,648.716	5.156	- 6.7	8	-6.0	-18.1	$\frac{1}{4}$

NORMAL PLACES

	Mean Phases		Mean Velocity	Weight	Residuals O-C	
	Pre- liminary	Final			Pre- liminary	Final
1.....	8.973	8.946	+ 83.2	2.0	+0.4	+4.4
2.....	10.350	10.323	+ 56.2	2.5	-0.6	-3.7
3.....	11.403	11.376	+ 14.1	1.0	+9.9	+5.5
4.....	12.179	12.152	- 46.5	1.0	-1.7	-1.9
5.....	.806	.779	-101.5	2.5	-6.0	-1.1
6.....	2.962	2.935	- 74.8	2.0	+6.7	+4.2
7.....	3.896	3.869	- 39.1	1.0	+9.3	+6.6
8.....	5.124	5.097	- 6.3	1.5	-4.4	-3.3
9.....	5.789	5.762	+ 15.8	2.0	-5.9	-2.7
10.....	6.851	6.824	+ 45.7	1.5	-8.1	-2.1
11.....	7.494	7.467	+ 66.4	1.5	-2.3	+4.5

Using the value of the period just mentioned the observations were grouped as the preceding table into eleven normal places, the weights of which were roughly as the number of lines measured in the plates comprising the group. It would have strengthened the solution if observations could have been secured near the phase 2.0 days but cloudy weather at those times prevented this being done. With the usual graphical methods employed here provisional values were adopted as follows:—

PRELIMINARY ELEMENTS

Period	$P = 12.427$ days
Eccentricity	$e = .15$
Longitude of periastron	$\omega = 120^\circ$
Velocity of system	$\gamma = -4.88$ km.
Semi-amplitude of range	$K = 95.0$ km.
Periastron passage	$T = \text{J.D. } 2,419,636.199$

Making the following transformations for the sake of homogeneity, eleven observation equations of the Lehmann-Filhés form were built up connecting the residuals with the five unknowns γ , K , e , ω and T .

$$\begin{aligned}
 x &= \delta\gamma \\
 y &= \delta K \\
 z &= K \delta e \\
 u &= K \delta \omega \\
 v &= \frac{K}{(1-e^2)^{\frac{1}{2}}} \mu \delta T \\
 &= [1.69636] \delta T
 \end{aligned}$$

OBSERVATION EQUATIONS FOR BOSS 5070

1	1.000x	+ .923y	- .386z	- .194u	+ .056v	-0.4 = 0
2	1.000	+ .649	+ .895	- .820	+ .739	+0.6
3	1.000	+ .035	- .865	-1.115	+1.225	-9.9
4	1.000	- .429	- .150	-1.068	+1.236	+1.7
5	1.000	- .954	-1.043	- .607	+ .607	+6.0
6	1.000	- .807	+ .835	+ .551	+ .636	-6.7
7	1.000	- .458	+ .932	- .794	+ .763	-9.3
8	1.000	+ .031	- .268	- .864	+ .740	+4.4
9	1.000	+ .280	- .217	- .805	- .679	+5.9
10	1.000	+ .618	- .828	+ .591	- .526	+8.1
11	1.000	- .774	- .976	+ .398	- .398	-2.3

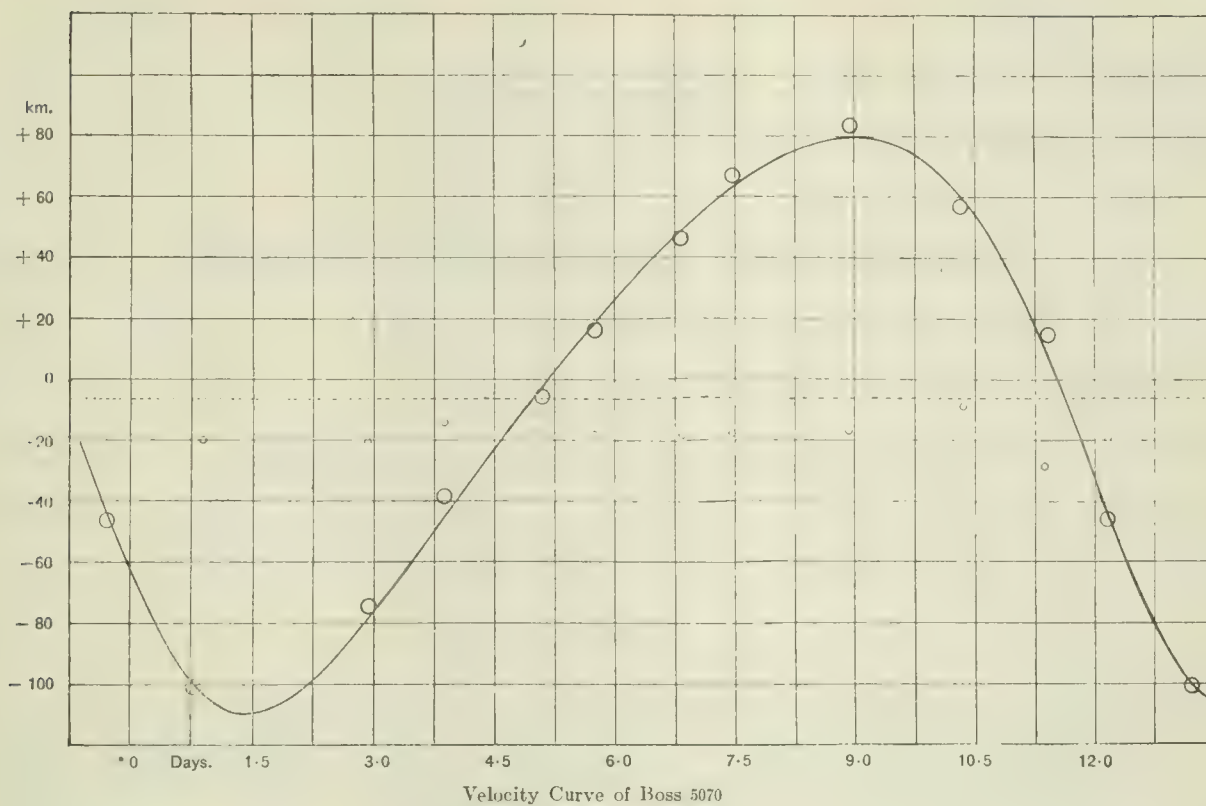
From these there resulted the following normal equations:—

$$\begin{aligned}
 18.599x + 1.389y - .563z + .149u + 6.342v + 18.800 &= 0 \\
 8.359 - .414 + .350 - 3.219 + 13.028 & \\
 10.713 - .565 + 4.504 - 56.889 & \\
 9.476 - 4.675 + 8.022 & \\
 9.110 - 26.363 &
 \end{aligned}$$

giving small corrections as follows:—

$$\begin{aligned}
 \delta\gamma &= -1.30 \text{ km.} \\
 \delta K &= -0.60 \text{ km.} \\
 \delta e &= +0.049 \\
 \delta\omega &= +0.08^\circ \\
 \delta T &= +0.027 \text{ days}
 \end{aligned}$$

The new values improved the agreement considerably, the sum of the squares of the residuals for the normal places being reduced from 573.6 to 256.4. The probable error of a plate, obtained from columns 6 and 7 of the table of observations, was lower than was at first thought likely, being ± 3.0 km. per sec. The accompanying graph represents the final elements showing the observations as grouped. The small circles signify the velocities of the K-line while the dotted horizontal line indicates the velocity of the centre of the system.



The following table gives the final values of the elements with their probable errors.

FINAL ELEMENTS

$$\begin{aligned}
 P &= 12.427 \text{ days} \\
 e &= .199 \pm .021 \\
 \omega &= 120.08^\circ \pm 1.29^\circ \\
 \gamma &= -6.18 \text{ km.} \pm 1.79 \text{ km.} \\
 K &= 94.40 \text{ km.} \pm 2.14 \text{ km.} \\
 T &= \text{J.D. } 2,419,636.226 \pm .076 \text{ days} \\
 a \sin i &= 15,808,000 \text{ km.} \\
 \frac{m_1^3 \sin^3 i}{(m + m_1)^2} &= 1.02 \odot
 \end{aligned}$$

Dominion Astrophysical Observatory,
 Victoria, B.C.
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THE SPECTROSCOPIC ORBIT OF α DRACONIS

BY R. K. YOUNG

α Draconis (R.A. 1900, $18^h 49.7^m$, dec. $+ 59^\circ 16'$ was announced as a spectroscopic binary from the Lick Observatory in 1910. Its spectral class is K and the lines are of very good quality. For a long time it has seemed to the writer that there is need for more orbits of late type stars for statistical purposes. Thus of the two hundred orbits determined there are less than 30 of later type than F. The reason for this small number is quite plain. Almost all the observatories determining binary orbits are using I-prism instruments and the late type stars do not usually have a sufficiently large range to enable accurate elements to be determined. The very satisfactory behavior of the I-prism spectrograph attached to the 72-inch telescope and the small probable errors obtained when the plates are measured on the Hartmann Comparator, however, make it quite possible to obtain good approximate elements for many of these stars. Observations have been started of the stars listed below in Table I. Many of them show evidence of periodicity already.

TABLE I

Star	R.A. 1920	Dec. 1920	Type	Star	R.A. 1920	Dec. 1920	Type
	h m	° '			h m	° '	
33 Piscium.....	00 01.2	- 6 19	K	4 Ursae Min.....	14 07.8	+77 55	K
ξ Piscium.....	01 49.2	+ 2 49	K	BD66° 878.....	14 56.3	+66 15	Ma
δ Trianguli.....	02 11.9	+33 52	G	Boss 4129.....	16 09.0	+36 38	K5
τ Persei.....	02 48.6	+52 26	Gp	Boss 4660.....	18 21.8	+ 8 00	K
ρ 17 Orionis.....	05 09.1	+ 2 47	K	β Scuti.....	18 42.9	- 4 50	G
16 Aurigae.....	05 12.9	+33 18	K	δ Sagittae.....	19 43.8	+18 20	Map
η 7 Geminorum.....	06 10.0	+22 32	Ma	ι Aquilae.....	20 34.2	- 1 23	K
Boss 2463.....	09 08.0	+61 45	F8	μ Cephei.....	21 40.8	+58 24	Ma
12 Coma Ber.....	12 18.5	+26 17	Gp	24 Cephei.....	22 08.3	+71 57	K

In all only 12 observations of α Draconis were secured at Victoria and the five observations taken at the Lick Observatory since 1902 and the two observations taken at Bonn in 1911 supplemented these in the most desirable way enabling both the shape and the period of the curve to be determined. The observations are listed in Table II.

TABLE II

Plate Number	Date	Julian Date G.M.T.	Phase from Final T	Velocity	O—C Final	O—C Prelim.
	1902					
Lick	July 14.....	2,415,945.757	9.68	— 6.40	—0.8	+ .4
	1907					
"	June 17.....	7,744.842	9.30	— 5.35	+0.6	+1.6
	1909					
"	June 30.....	8,488.797	61.16	—14.81	—0.6	—2.0
"	July 7.....	8,495.881	68.24	—20.16	+0.1	—1.3
	1911					
Bonn	Aug. 8.....	9,257.36	137.62	—16.0	+2.6	+2.4
"	" 9.....	9,258.36	138.62	—18.4	—1.0	—1.2
	1920					
Victoria						
4513	June 30.....	2,422,506.841	65.02	—17.9	—0.4	—1.3
4645	July 18.....	2,524.828	83.01	—31.2	+1.0	+0.8
4695	" 25.....	2,531.799	89.98	—40.6	—3.6	—3.4
4735	" 28.....	2,534.800	92.98	—38.4	+0.2	+0.4
4753	Aug. 1.....	2,538.796	96.98	—39.4	+1.1	+1.5
4818	" 8.....	2,545.790	103.97	—42.5	+0.3	+0.5
4935	" 25.....	2,562.800	120.98	—37.9	—0.3	—0.9
4991	Sep. 1.....	2,569.747	127.93	—31.0	—0.0	—1.1
5128	" 29.....	2,597.692	17.47	+ 1.5	+0.5	+1.5
5210	Oct. 14.....	2,612.589	32.37	+ 3.3	—0.4	+0.5
5363	" 31.....	2,629.584	49.36	— 4.5	+0.4	+0.0
5494	Nov. 18.....	2,647.593	67.37	—18.3	+1.2	+0.4

An approximate period of 138.4 days was deduced from the observations and the early measures when plotted with this period are well represented. It was advisable to include the period in the least-squares solution made for the final elements. The two observations taken in 1909 at the Lick Observatory were grouped into one normal place. The two Bonn observations were similarly treated and also the observations of July 25 and 28 made at Victoria. This gives 15 normal places. All the normal places were given the same weight save the one formed from the two III-prism plates of the Lick Observatory which was given weight 2. In effect this gives the early III-prism plates the same weight as the recent I-prism. This was done because the majority of the observations were made at Victoria and it was felt that the shape of the curve should rest primarily on the recent observations. To have given the early observations the weight which their accuracy justifies would, in view of possible systematic differences between results at the two observatories, have had a disturbing effect on the elements.

The following preliminary elements were selected as a basis for a least-squares solution.

$$\begin{aligned} P &= 138.4 \text{ days} \\ e &= 0.10 \\ \omega &= 255^\circ \\ T &= \text{Julian Day } 2,419,251.38 \\ \gamma &= -19.53 \text{ km.} \\ K &= 23.15 \text{ km.} \end{aligned}$$

These elements yield the residuals given in the final column of the table of observations. For the normal places the Σpv^2 was 19.6.

OBSERVATION EQUATIONS

1	1.000x	+	.546y	+	.917z	+	1.046u	-	.930v	-	1.025w	-	.410	=	0	Wt. 1
2	1.000	+	.541	+	.920	+	1.046	-	.933	-	.469	-	1.570			1
3	1.000	+	.154	-	.887	-	.107	+	.797	+	.202	+	1.600			2
4	1.000	+	.072	+	1.092	+	.480	-	1.191	+	.000	-	.580			1
5	1.000	+	.121	-	.892	-	.042	+	.803	-	.871	+	1.250			1
6	1.000	-	.542	-	.760	+	.944	+	.743	-	.811	-	.800			1
7	1.000	-	.803	-	.532	+	.879	+	.579	-	.633	+	1.460			1
8	1.000	-	.930	-	.331	+	.583	+	.413	-	.453	-	1.580			1
9	1.000	-	1.019	-	.024	-	.015	+	.124	-	.136	-	.540			1
10	1.000	-	.760	+	.776	-	1.022	-	.799	+	.882	+	.860			1
11	1.000	-	.453	+	1.001	-	.603	-	1.090	+	1.206	+	1.060			1
12	1.000	+	.841	+	.595	+	.728	-	.524	+	.584	-	1.480			1
13	1.000	+	.962	-	.057	-	.537	+	.142	-	.159	-	.480			1
14	1.000	+	.645	-	.645	-	.911	+	.616	-	.693	-	.020			1
15	1.000	+	.034	-	.901	+	.127	+	.812	-	.919	-	.360			1

$$\begin{aligned} \text{where } x &= \delta\gamma & u &= K \delta e \\ y &= \delta K & v &= \frac{K \mu}{(1-e^2)^{\frac{3}{2}}} \delta T \\ z &= K \delta \omega & \omega &= \frac{3000 K}{(1-e^2)^{\frac{3}{2}}} \delta \mu \end{aligned}$$

These yield the following normal equations

$$\begin{aligned} 16.000x - 0.437y - 0.615z + 2.489u + 0.359v - 3.093w + 0.010 &= 0 \\ +6.332 + 0.820 - 0.045 - 0.912 - 0.705 - 2.056 &= 0 \\ +9.410 + 0.835 - 9.315 + 3.676 - 4.828 &= 0 \\ +7.519 - 0.718 - 3.757 - 5.494 &= 0 \\ +9.300 - 3.682 + 4.184 &= 0 \\ +7.317 + 2.821 &= 0 \end{aligned}$$

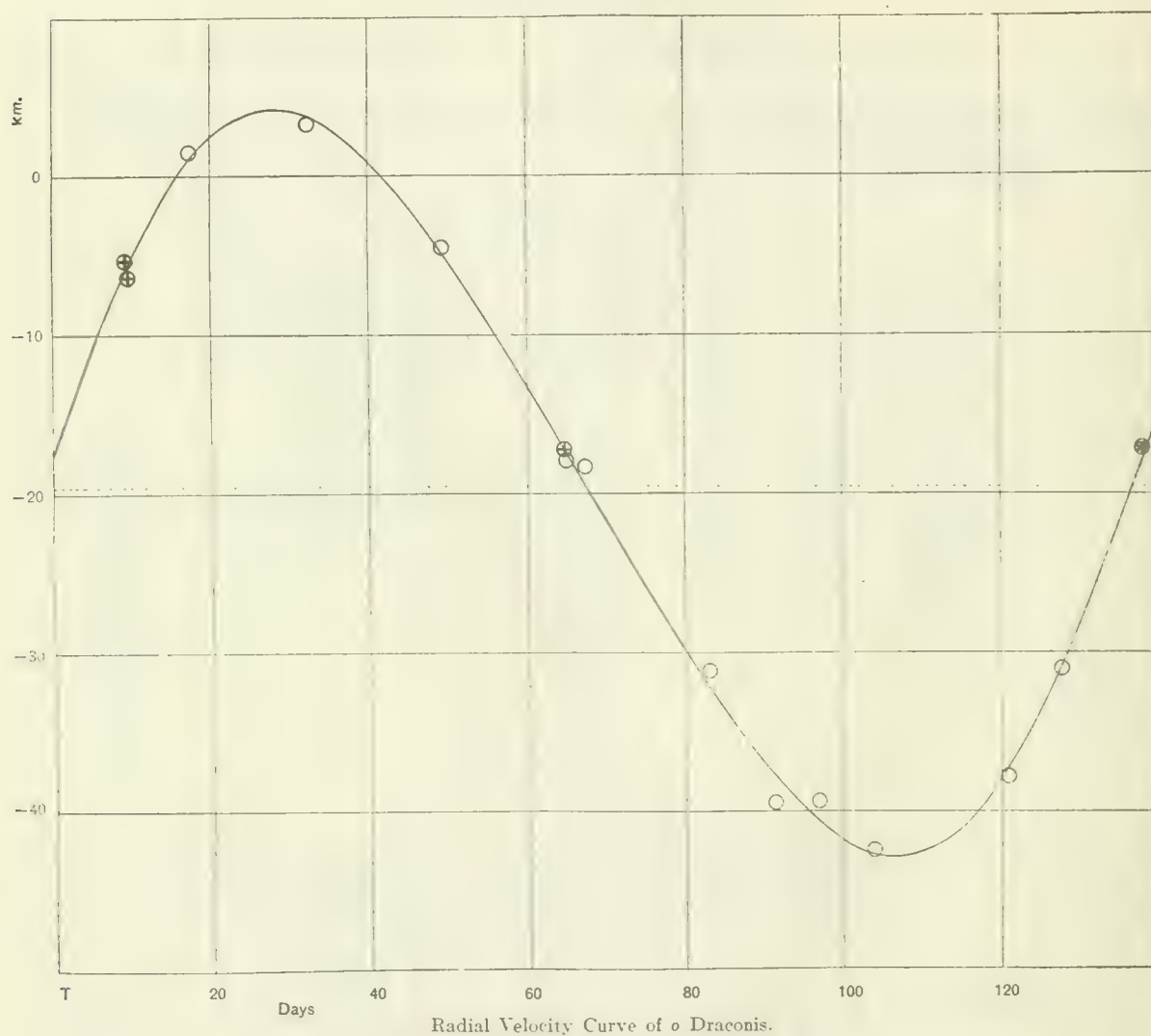
and these give

$$\begin{aligned} x &= +.005 & \text{or } \delta\gamma &= +.005 \text{ km.} \\ y &= +.307 & \delta K &= +.31 \text{ km.} \\ z &= +7.80 & \delta\omega &= +19.31^\circ \\ u &= +0.321 & \delta e &= +.014 \\ v &= +7.23 & \delta T &= +6.78 \text{ days} \\ w &= -0.469 & \delta P &= +.020 \text{ days} \end{aligned}$$

The final elements with their probable errors are

Period	$P = 138.420 \text{ days}$	$\pm .016$
Eccentricity	$e = 0.114$	$\pm .014$
Longitude of periastron	$\omega = 274.31^\circ$	$\pm 6.36^\circ$
Periastron passage	$T = \text{J.D. } 2,419,258.16$	$\pm 2.43 \text{ days}$
Velocity of system	$\gamma = -19.525 \text{ km.}$	$\pm 0.21 \text{ km.}$
Semi-amplitude	$K = 23.46 \text{ km.}$	$\pm 0.30 \text{ km.}$

The residuals were reduced considerably and Σpv^2 came out 9.3 as compared with 19.6 for the preliminary elements. The probable error for a normal place of weight unity was 0.68 km. The probable error for a single I-prism observation taken at Victoria is 0.81 km. and if we omit the third observation which has an unusually high residual we obtain the low value 0.67.



The normal places are plotted on the graph showing the radial velocity curve. The Lick observations are the circle and cross. The Bonn observations the filled circle and the others are the I-prism observations with the 72-inch telescope.

Dominion Astrophysical Observatory,
Victoria, B.C.

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THE SPECTRUM OF NOVA CYGNI 1920

WITH A

NOTE ON THE SPECTRUM OF NOVA AQUILAE No. 3

BY W. E. HARPER

On August 20th, 1920, a new star was discovered in the constellation Cygnus by Denning, of Bristol, England, while he was engaged in observing and plotting meteor trails. The announcement was cabled to Harvard the following day, but did not reach here until the 23rd. For the six weeks or so previous practically every night had been clear, but a spell of cloudy weather set in about that time which greatly interfered with the observation of the star. Then, too, the cloudy spell interfered with our regular observing program of Boss stars, which became crowded in the early evening hours, and as a consequence the nova was not observed as frequently as would otherwise have been the case. Nevertheless, 19 plates on 12 nights from August 24 to September 28 furnish considerable data, which the following discussion aims to summarize.

The spectra were made with the single prism spectroscope attached to the 72-inch reflector. It had been intended to use a three-prism dispersion if the sharp line stage, noted in former novæ, should be recorded. Such was not the case here on any night in which the star was observed, though from reports such a stage was recorded in England. Sixteen of the spectra were made on Seed 30 emulsion with a medium focus camera, giving a range of spectrum roughly from $\lambda 3700$ to $\lambda 5150$ with a dispersion of 25.7 angstroms per millimetre at $\lambda 4200$, the centre of the plate. The remaining three spectra were made on Ilford Panchromatic plates with a shorter focus camera, taking in a range of spectrum from $\lambda 3700$ to $\lambda 6800$ and having a dispersion of 43.4 angstroms per millimetre at $\lambda 4200$.

From photographic records there seems to have been no star occupying the exact position of the nova—at least none brighter than the 17th magnitude. As it attained a maximum on August 23rd equal to a 2nd magnitude star, it thus increased in brightness

over 15 magnitudes and therefore, while less brilliant at maximum than Nova Aquilæ, it outrivalled it in the extent of its variation. Estimates of its magnitude were made here by the writer when clear weather permitted, either with the naked eye or with binoculars, or sometimes with the 4-inch finder of the telescope. Dr. R. K. Young also kept a record of its magnitude from night to night and, though made quite independently of one another, the naked-eye estimates generally agreed to 0.1 magnitude. The nova was compared with the surrounding stars, the magnitudes of these being taken from Harvard Annals, Volume 50. My own observations, limited in number as they are, are given below.

MAGNITUDE OF NOVA CYGNI

1920,	Aug.	24.7	2.1	glimpsed through clouds
	"	25.7	2.3	
	"	27.7	3.4	
	"	29.7	3.9	
	"	30.7	4.1	little haze
	"	31.7	4.2	
	Sept.	1.7	4.3	
	"	3.7	4.6	
	"	6.7	4.8	
	"	7.7	4.8	
	"	24.7	6.5	brick red
	"	27.7	7.0	observed by J. S. P. Very red
	"	28.7	7.2	very red on slit

While our observations are entirely too few to decide the matter, yet, so far as they go, they do not reveal any oscillations in brightness so marked in Nova Persei and in Nova Aquilæ. The decline was very rapid but continuous.

GENERAL DESCRIPTION OF THE SPECTRUM

The plates of August 24 showed a strong continuous spectrum with broad absorption lines of hydrogen displaced toward the violet corresponding to a velocity of 650 km. per sec. approach—the equivalent of 9 angstroms at the $H\gamma$ region. Broad but faint and more elusive absorption lines which could be identified with enhanced lines of iron and other elements, were also present with displacements similar to the hydrogen lines. The H and K lines of calcium were especially strong and similarly shifted. As there seems to be some difference of opinion as to when emission first made its appearance, it may not be amiss to record that there seems no reasonable doubt of its presence on our plates of this night at G.M.T. 16½ hours. Its presence at $H\gamma$ and farther to the violet is open to question, but at $H\beta$ and at the enhanced lines at $\lambda 4924$, $\lambda 5018$ and $\lambda 5169$ there is a decided strengthening of the continuous spectrum which is unmistakable. Fine sharp H and K lines of calcium undisplaced were also a feature of the spectra as in other recent novæ.

The development of the spectrum during the remaining days of August and the first few days of September was marked by the formation of the usual nova emission bands,

their increase in intensity relative to the continuous spectrum, and by the increase in the displacement of the absorption bands. From a displacement of 9 angstroms (referred to $H\gamma$) on Aug. 24 this increased to 12 on Aug. 25, to 16 on Aug. 27, and seemed to reach a maximum of a little over 17 by the end of the month, the displacement being, as is always the case, to the violet of the normal position of the lines. The equivalent velocities of these displacements are quoted in the Summary of Measures, from which it is seen that if these represent the velocities of the expanding shell of gas then they increased in the interval mentioned from 650 km. to nearly 1200 km. per sec. As already stated, there is some doubt as to the presence of emission bands to the violet of $H\gamma$ on August 24, but they are quite pronounced on plates of the 25th and by the 27th there is a marked difference between the emission and continuous spectrum. On plates of this latter date, while all the emission bands show evidences of structure, yet it is most pronounced in the case of the hydrogen bands, they having two maxima at the sides with faint absorption between. A peculiarity of this structure is that in the case of hydrogen the absorption divides the emission band unsymmetrically, there being more of it to the violet than to the red. The plate taken the last week of September showed that the light from the star was mostly concentrated in the emission bands, $\lambda 4640$ being prominent.

The emission lines were strongest at the red end and rapidly became fainter as the violet was approached. On a panchromatic plate taken on Sept. 2 with a dispersion such that from $H\alpha$ to K was 32 mm, the red $H\alpha$ line is a very outstanding feature of the spectrum. This band is the probable cause of the strong orange colour to the telescopic image during the latter part of September. The widths of the emission bands are much less than was the case in Nova Aquilæ. The three bands to the red of $H\beta$, namely the enhanced lines of iron at $\lambda\lambda 5169$, 5018 and 4924, and $H\beta$ itself are each about 28 angstroms in width, $H\gamma$ 23, $H\delta$ 19 and K 18 angstroms in width. In the case of $H\alpha$ there is no doubt of a decided increase in its width between Aug. 25 and Sept. 2, it being very noticeable from even a casual inspection of the plates. If anything its centre is more to the red on the latter date than on the former, but no great weight is attached to this owing to the low dispersion used and the band may be considered as occupying its normal position.

In one particular at least the spectrum differs from the general trend in Nova Aquilæ in that the main nebular bands N_1 ($\lambda 5007$) and N_2 ($\lambda 4959$) are not present on any of our plates, although a month had elapsed from the star's maximum brightness. In the case of Nova Aquilæ No. 3, whose decline in brightness was much less rapid, only about 9 or 10 days elapsed after the star started to wane before the N_1 band appeared and it was followed within the month's time by the other nebular bands at $\lambda 4363$ and at $\lambda 4959$.

WIDTHS AND POSITIONS OF THE MAIN EMISSION BANDS

An attempt has been made to determine if the main emission bands occupy their normal positions or if they have suffered any displacement, but owing to the lack of definition of their edges, the determinations are not very trustworthy. The following tables, however, give the results, which may be considered as approximate values at

least. The width of the bands is quoted in angstroms, while the displacements are quoted in their equivalent velocities. The mean of all measures indicates a velocity of recession of 31 km. per sec., the equivalent of a redward displacement of 0.5 angstrom at $H\beta$. Owing to the very large probable error of the determination, however, I do not look upon this as having any real significance, and prefer to consider the bands as occupying approximately their normal positions.

WIDTH OF EMISSION BANDS

(In Angstroms)

Plate	$H\alpha$	5169	5018	4924	$H\beta$	$H\gamma$	$H\delta$	K
4934.....	26.0			28.4	31.9	28.5	17.3	
4942.....		26.3	27.4	27.7	29.4	26.1		
5011.....	40.8	35.5	25.3	26.4	23.5	24.2	20.2	18.6
5052.....			26.9	28.4	34.0	24.0	20.1	17.0
5081.....			20.6	24.3	32.2	22.1	19.2	
5093.....	39.0				22.5	18.6	17.2	
5111.....					22.6	14.7		
Means.....		30.9	25.0	27.0	28.0	22.6	18.8	17.8

DISPLACEMENTS OF EMISSION BANDS

(km. per sec.)

Plate	5169	5018	4924	$H\beta$	$H\gamma$	$H\delta$	K
4929.....		+106	- 71	- 51			
4932.....		- 58	+190	+ 74	+170		
4933.....		-196	+174				
4934.....		+135	+185	- 19			
4938.....		+ 73	+ 27	+123	+ 32	- 4	
4939.....		- 88	+ 23	+140			
4942.....	- 10	- 2	+ 24	- 29	+ 77		
5011.....	+ 46	+ 35	+ 11	+ 6	+ 83	+ 29	- 35
5052.....	- 89	- 30	+ 51	- 34	+ 20	+ 80	
5081.....			+ 24	+105	+131	+124	
Means.....	- 18	- 33	+ 64	+ 35	+ 85	+ 57	- 35

Mean of 42 measures on 10 plates = + 31 km. per sec.

= + 0.5 angstroms at $H\beta$

MEASURES OF ABSORPTION BANDS

Plate	Camera	Date G. M. T.	Velocity Absorption	Lines	Wt.	Sharp H and K	Wt.
4928	Im	1920, Aug. 24.694.....	- 645	8	$2\frac{1}{2}$	-15.2	6
4929	"	" 24.707.....	- 663	11	$2\frac{3}{4}$	-17.4	6
4932	"	" 25.716.....	- 797	8	$1\frac{5}{8}$	-19.6	5
4933	"	" 25.731.....	- 879	8	$2\frac{3}{4}$	-16.6	6
4934	Is	" 25.760.....	- 847	9	2	-19.3	3
4938	Im	" 27.704.....	-1103	7	$1\frac{3}{8}$	-15.5	6
4939	"	" 27.716.....	-1099	8	2	-17.1	5
4942	"	" 29.660.....	-1077	8	$1\frac{3}{8}$	-17.2	6
4943	"	" 29.684.....	-1135	2	$\frac{1}{2}$	-16.4	6
4960	"	" 30.710.....	-1111	2	$\frac{1}{2}$	-19.1	5
4961	"	" 30.716.....	-1190	2	$\frac{1}{2}$	-18.0	6
4977	"	" 31.744.....	-1110	2	$\frac{1}{2}$	-17.2	6
4989	"	Sept. 1.715.....	-1218	2	$\frac{1}{2}$	-15.4	5
5010	"	" 2.759.....	-1196	2	$\frac{1}{2}$	-14.7	6
5011	Is	" 2.778.....	-1164	3	$\frac{1}{4}$	-16.0	1
5052	Im	" 6.777.....	-1185	3	$\frac{3}{4}$	-18.0	6
5081	"	" 24.765.....	.....	.....	.....	.....	.....
5093	Is	" 27.753.....	.....	.....	.....	.....	.....
5111	Im	" 28.727.....	.....	.....	.....	.....	.....

The foregoing table summarizes the measures of the absorption bands. At the first, 9 or so of the best of the broad bands were used, but by the end of August, as their positions seemed to undergo no further change, only two or three of the best were measured. These latter results will hence not have quite the accuracy of the first eight, but they will closely approximate the correct values as the interagreement was good. The principal bands besides the hydrogen ones and the calcium H and K were the enhanced iron lines at $\lambda\lambda 5169$, 5018 and 4924. Others were measured and their wave lengths calculated on the assumption that they had suffered displacements similar to the known ones. Thus on the plate of Sept. 6 the following broad absorption bands were present:

4623	4476
4586	4472
4555	4450
4497	4424

SHARP H AND K CALCIUM ABSORPTION

Attention has been called to the fine, undisplaced calcium lines, and the foregoing table also contains the measures of the 16 plates on which the lines are seen. The velocity appears to be quite constant with a mean value -17.0 ± 0.25 km. per sec., practically identical with the component of the solar motion in that direction. Thus, if these lines,

by their position, indicate the real motion of the star, it is practically at rest with respect to the stellar system. Such, of course, was found to be the case in Nova Persei 1901, Nova Geminorum 1912, and Nova Aquilae 1918.

MAIN FEATURES OF SPECTRUM FROM $H\alpha$ TO K

A detailed list of the emission and absorption features of two spectra taken with the short-focus camera are appended. The positions of the various bands were computed by the aid of a Hartmann interpolation formula to the first decimal place of an angstrom and then rounded off to the nearest whole number. Taken in conjunction with the photographs accompanying the article a very fair idea of the spectrum can be had.

DETAILED SPECTRUM

Plate 4934 1920, Aug. 25

absorption line.....	6871	absorption.....	4817
strong emission $H\alpha$	6557	absorption.....	4756
absorption band $H\alpha$	6542	broad absorption.....	4606
narrow absorption.....	6382	absorption.....	4540
emission 20 A wide.....	6195	absorption.....	4495
absorption.....	6142	very broad absorption.....	4472
indefinite absorption.....	5949	very broad absorption.....	4458
wide absorption.....	5880	very broad absorption.....	4434
narrow absorption.....	5595	broad absorption.....	4408
absorption (?).....	5519	broad absorption.....	4388
broad absorption.....	5300	$H\gamma$ emission 29 A wide.....	4345
broad absorption.....	5261	$H\gamma$ absorption.....	4328
very broad absorption.....	5216	very broad absorption.....	4284
absorption (5169).....	5156	absorption.....	4219
emission (5018).....	5016	$H\delta$ emission.....	4100
absorption (5018).....	5004	$H\delta$ absorption.....	4090
emission (4924).....	4927	sharp calcium H abs.....	3968
absorption (4924).....	4911	broad abs. H and He	3958
emission $H\beta$	4861	sharp calcium K abs.....	3934
absorption $H\beta$	4846	broad K absorption.....	3923

Plate 5011

Sept. 2, 1920

H α emission.....	6563	absorption narrow.....	5184
em. ft., 33 A wide.....	6458	emission 36 A wide.....	5170
absorption.....	{ 6440	emission 25 A wide.....	5019
	6389	emission 26 A wide.....	4924
em. 40 A wide.....	6367	emission H β 24 A wide.....	4862
absorption.....	{ 6350	absorption central.....	4864
	6318	absorption 14 A wide.....	4840
emission 28 A wide.....	6302	emission edge diff. band.....	{ 4691
absorption.....	{ 6288	emission strongest.....	{ 4627
	6260	emission edge band.....	{ 4620
emission 26 A wide.....	6244	absorption strong.....	4605
absorption.....	{ 6229	emission 23 A wide.....	4584
	6170	absorption uniform.....	4566
emission 22 A wide.....	6159	emission 20 A wide.....	4549
em. v. ft. broad.....	6001	absorption.....	4537
absorption band.....	5974	emission broad.....	4519
em. strong, 34 A wide.....	5900	emission.....	4484
absorption narrow D (?).....	5897	absorption.....	4478
absorption.....	5878	emission.....	4463
emission faint.....	5652	absorption weak.....	4456
absorption band.....	{ 5640	absorption definite.....	4431
	5582	absorption 12 A wide.....	4375
emission.....	5578	emission H γ 24 A wide.....	4342
absorption 21 A wide.....	5556	absorption central.....	4344
emission.....	5532	emission faint 18 A wide.....	4300
emission very faint.....	5422	abs. faint 20 A wide.....	4282
em. faint 25 A wide.....	5365	emission 14 A wide.....	4234
em. strong 28 A wide.....	5318	emission 15 A wide.....	4176
absorption strong.....	5297	emission H δ 20 A wide.....	4102
em. strong 27 A wide.....	5277	emission H and H γ broad.....	3971
absorption.....	5255	absorption narrow H.....	3968
emission 23 A wide.....	5234	emission K, 19 A wide.....	3933
absorption.....	5216	absorption narrow K.....	3933
emission irreg. 22 A wide.....	5194		

The illustrations used are direct enlargements of the spectrum plates, the magnification being 5.4 diameters. Being prints of enlargements of the original negatives, they are, of necessity, negatives themselves.

While the writer is responsible for the measurement and discussion of the plates, all of the observers shared in the work of securing them.

Dominion Astrophysical Observatory,
Victoria, B.C., Jan. 14, 1921.

NOTE ON THE SPECTRUM OF NOVA AQUILÆ No. 3

The following note contains a brief description of the character of the spectrum on four dates in 1919 and one in 1920, and includes also a more definite determination of the position of the $H\beta$ emission band in 1918.

The new plates were taken at this observatory with the single prism camera in general use, using Seed 30 plates. They are as follows:

Plate No.	Date G. M. T.	Exposure	Mag.	Remarks
2087	1919, June 3.927.....	20 ^m	7 \pm	image very blue
2155	.... June 18.878.....	60 ^m		
2473	.... July 21.818.....	40 ^m	7.0	
2925	.... Sept. 12.696.....	60 ^m	7.5	image "electric" blue
4149	1920, April 23.986.....	60 ^m		

Since the autumn of 1918 the spectrum of the nova has undergone slight modifications in the region covered by our plates, namely from $\lambda 3900$ to $\lambda 5100$. These changes may be summed up by stating that the hydrogen emissions have vanished—disappearing first from the violet end of the spectrum—and the nebular emissions are more complicated by reason of numerous absorption lines crossing the bands. The emission band, which extended roughly from $\lambda 4600$ to $\lambda 4700$, was very faint in 1919 relative to the other emission bands, and barely a trace of it is seen on the 1920 plate, although all plates could with profit stand more exposure. The continuous spectrum, which at the close of 1918 was almost a negligible quantity, was fairly strong on the plates of June, 1919, but became very weak on the remaining plates. Whether this variation was co-incident with variations in its light similar to that of July, 1918, cannot be stated, as definite determinations of its brightness were not made here. The magnitudes quoted in the table above are very rough estimations, probably within 0.5 m., but it will probably be found when the definite light curve for that year is published that there is such a connection between the two phenomena.

The main portions of the N_1 and N_2 emission bands are well defined, about 12 angstroms in width, with centres at 5007.3 and 4959.5 respectively. The 4363 band is about 55 angstroms wide and its centre is approximately 4364. A noticeable feature of the spectrum is the presence of narrow, apparently isolated, emission strips about 27 angstroms to the violet of the normal position of the bands. Interpreted as velocity displacements they represent an approach of 1750 km. per sec. and thus are identical in position with the least displaced set of absorption lines when they reached their maximum displacement about the end of June, 1918. The impression one gets from a casual inspection of these bands is that these isolated strips are really the violet edges of bands approximately 55 angstroms in width, which have been "eaten out" by absorption, leaving only these strips and the central section of 12 angstroms width.

The measures of these isolated strips on the assumption that they are velocity displacements are given in the following table, plate No. 1041, taken 1918, Dec. 15, being added for reference. The velocities are reduced to the sun only and in computing them I have used the wave-lengths for the nebular bands as given by Wright in Volume 13 of the *Lick Observatory Bulletin*.

NARROW EMISSION STRIPS

	1041	2087	2155	2473	2925	4149
5007·02	-1659·0	-1755·0	-1763·4	-1751·4	-1733·8	-1749·2
4959·09	-1658·5	-1761·0	-1744·0	-1737·9	-1727·6	-1759·2
4861·53	.....	-1739·	-1748·2	.....	.....	.....
4363·37	.....	-1772·2	-1765·3	-1740·5	-1739·1	.....
Mean.....	-1658·8	-1756·5	-1755·2	-1743·3	-1733·5	-1754·2
Reduction to sun	- 10·6	+ 12·6	+ 6·3	- 8·5	- 26·2	+ 24·5
Velocity.....	-1669	-1744	-1749	-1752	-1760	-1730

MAIN EMISSION BANDS

Band	1041	2087	2155	2473
N ₁	5007·2	5007·6	5006·8	5007·2
N ₂	4959·2	4959·3	4959·7	4959·5
H β	4860·0	.....	.....	.....
4363.....	4362·8	4364·6	4364·6	4364·6

The wave lengths of the foregoing bands were obtained by measuring their edges' reducing to wave lengths by a Hartmann interpolation formula, and making correction for the reduction to the sun and also allowing for the shift due to the 20 km. approach of the nova. While the N₁ and N₂ bands are fairly definite, the main intense portions being 12 or 13 angstroms in width, the 4363 band is 55 angstroms wide and its determination is subject to considerable error.

The emission bands become complicated by reason of being crossed by numerous lines, apparently due to some absorbing matter between us and the emission producing substance. One of these absorption lines has been singled out, not only because it is one of the most prominent, but also because of its presence in the hydrogen emission bands all through the latter part of 1918. From the Ottawa spectrograms the writer found the corresponding velocity to be -446 km. per sec., referred to the sun. Lunt and others have since got almost identical results. While the line is not quite so well measurable in these as in the 1918 plates, due mostly to the less dense spectra obtained when the star was faint, yet there is no doubt that it is similar absorption which has made its appearance in the nebular bands.

CHARACTERISTIC ABSORPTION LINE IN EMISSION BANDS

	1041	2087	2155	2473	2925
5007.02	.....	-480.6	.....	-479.4	-445.2
4959.09	.....	-476.7	-483.6	-451.5	-440.5
4861.53	-450.8	.....	-468.8	.....	.....
4363.37	-431.4	-461.0	-430.7	-437.6	.....
Means.....	-441.1	-472.8	-461.0	-456.2	-442.8
Reduction to sun.....	- 10.6	+ 12.6	+ 6.3	- 8.5	- 26.2
Velocities.....	-452	-460	-456	-465	-469

MISCELLANEOUS ABSORPTION LINES

1041	2087	2155	2473	2925	4149	Mean
.....	.....	.....	.....	5036.5	5036.9	5036.7
.....	.....	.....	.....	5028.6	5028.8	5028.7
.....	.....	.....	.....	.....	5022.5	.....
.....	.....	.....	.....	.....	5016.5	.....
.....	.....	.....	.....	.....	4993.5	.....
.....	.....	.....	4988.3	4988.2	4987.4	4988.0
.....	.....	.....	4983.0	4983.2	.....	4983.1
.....	4669.0	.....	.....	.....	.....	.....
.....	4655.2	.....	.....	.....	.....	.....
.....	4549.7	.....	.....	.....	.....	.....
.....	4388.6	4388.5	4389.1	.....	.....	4388.7
.....	4385.3	.....	.....	.....	.....	.....
4382.8	4382.0	4382.8	4382.4	.....	.....	4382.0
.....	.....	4381.4	.....	.....	.....	.....
4376.9	4377.3	4377.4	.....	.....	.....	4377.2
.....	.....	4375.2	.....	.....	.....	.....
.....	.....	4374.7	.....	.....	.....	.....
4371.0	4371.9	.....	4372.2	.....	.....	4371.7
.....	4369.5	.....	4369.2	.....	.....	4369.4
.....	4347.3	.....	.....	.....	.....	.....
.....	4343.5	.....	4342.6	.....	.....	4342.0
.....	4330.7	.....	.....	.....	.....	.....
.....	.....	4341.1	.....	.....	.....	.....

THE EMISSION BAND AT $H\beta$

In Volume IV, page 273, of the Publications of the Dominion Observatory, the writer gave a summary of the emission spectrum of Nova Aquilae No. 3, wherein he found the emission band at $H\beta$ to be about 54 angstroms in width with its centre displaced about 1 angstrom to the violet of its normal position. This was based on 28 plates taken

at Ottawa between July 19 and November 10, 1918, the plates earlier than these indicating a displacement of 0.4 angstrom, but with limits poorly determined. Had these earlier plates been included, the mean displacement would have been in the neighbourhood of 0.8 angstrom. Though the positions of the other bands were more or less roughly measured, this was the only one whose limits seemed sufficiently definite to base any conclusions upon.

In the case of Nova Aurigae 1892, while the literature on the subject is often contradictory, the results of Campbell, whose authority seems the best, showed that the emission bands were displaced to the violet 4 or 5 angstroms, though at times they were recorded much nearer their normal positions. But in recent cases, such as Nova Persei 1901 and Nova Geminorum 1912, where it is only natural to expect more accurate determinations, the emission bands were about 1 angstrom to the red in each case. This circumstance of a negative displacement in Nova Aquilae seemed to impress itself on the writer, and on coming to Victoria a few preliminary measures were made on the plates here with somewhat similar results.

Adams finds corroboration of this violet displacement on the Mount Wilson plates, as recorded in *Astrophysical Journal* for March, 1920, page 126. Lunt discusses the emission spectrum at some length in *Monthly Notices* for March, 1920, and gives results for the 3 hydrogen bands β , γ and δ , as well as for the nebular bands N_1 and N_2 . He finds an average displacement represented by -51.6 km. per sec., the equivalent at $H\beta$ of 0.84 angstroms to the violet. His displacement at $H\beta$ alone is 0.94 angstroms, but this is not comparable to my result because of a correction which I made—and which Dr. Lunt preferred not to make—namely, that required for the 20 km. per sec. approach as adduced from the sharp H and K lines. The concensus of opinion among astronomers, I believe, has been to regard these very fine, sharp calcium lines as reversals indicating the true velocity of the star. On such an assumption a correction of $+0.31$ angstroms would be required to Lunt's displacement, making it 0.63 angstroms. Lunt considers this view erroneous and looks upon the broad emission bands as giving the true velocity of the nova, namely, -51.6 km. per sec.

The purpose of this note is, however, not to discuss this phase of the question, but to give the results of additional measures. Looking over Lunt's results, I began to wonder if I had been too hasty in considering that no reliance could be placed on measures of the other bands. To that end I have examined many of the Victoria plates and 41 plates taken at Ottawa between July 1 and November 30, which the Director, Dr. Klotz, was kind enough to send me, and have not felt like changing my former opinion that measures made upon the other bands are only rough approximations at best. True, the nebular lines are occasionally definite, but the comparison lines are not always of the best. In the early stages $H\gamma$ is sharply defined by the absorption line at its violet edge and fades off very gradually into the continuous spectrum at its red edge and later it becomes blended with the nebular band $\lambda 4363$, so that uncertainty prevails in either case. However, occasion has been taken to measure $H\beta$ again on the 41 Ottawa plates

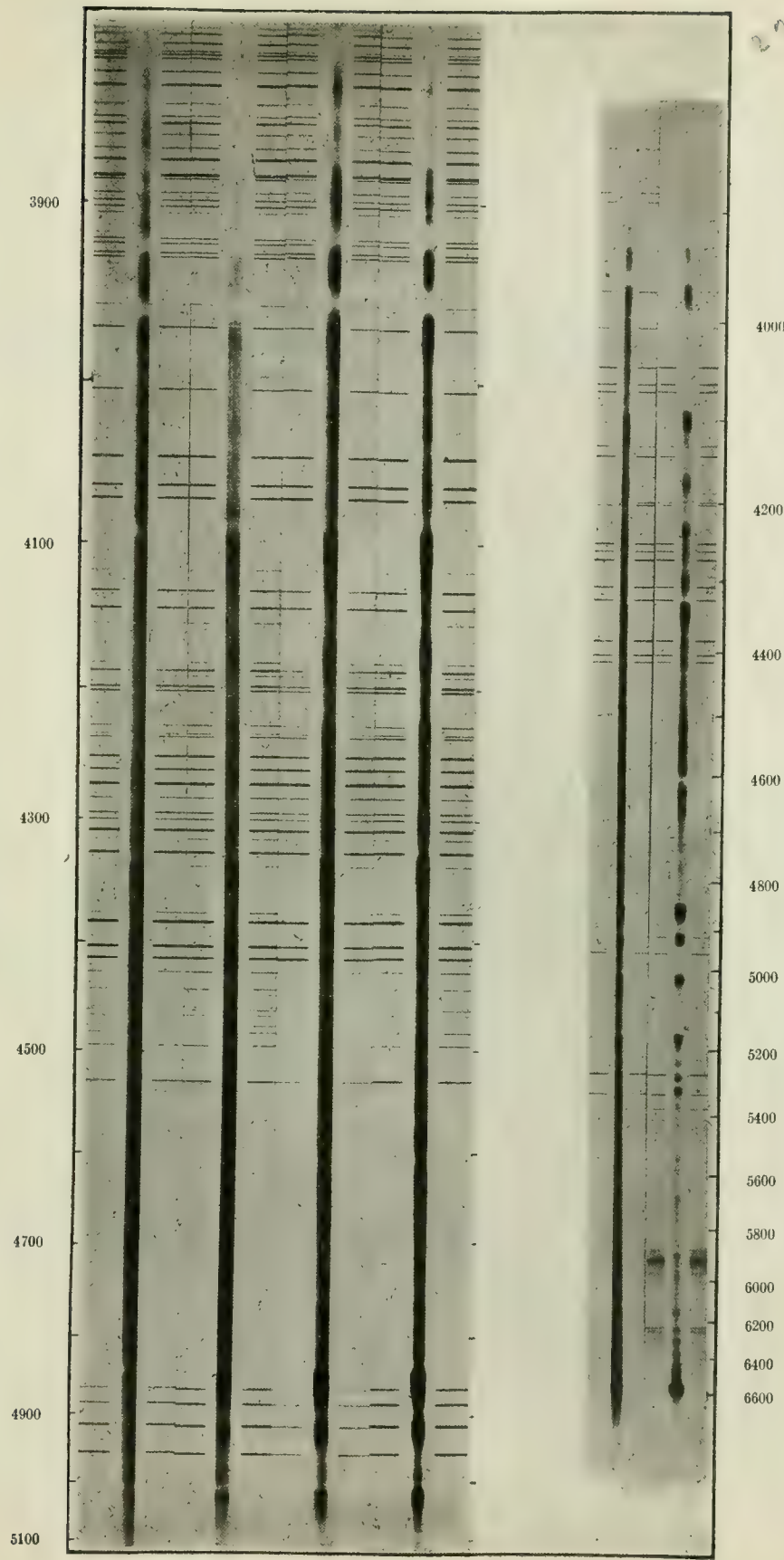
and on 20 Victoria plates as well covering practically the same interval, with the following result:

20 Victoria plates.....	4860.420
41 Ottawa plates.....	4860.466

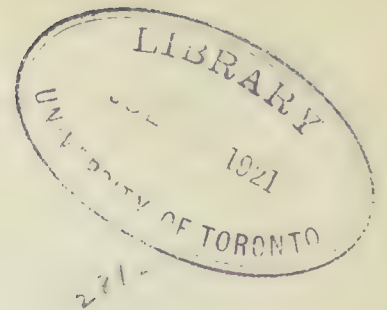
The weighted mean, when correction is made for the 20 km. approach, is 4860.76 ± 0.04 , and represents a negative displacement of 0.77 angstroms, approximately the same as the former but less extensive measures.

Dominion Astrophysical Observatory,
Victoria, B.C.,
December 30, 1920.

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SPECTRA OF NOVA CYGNI 1920
Taken at the Dominion Astrophysical Observatory, Victoria, B.C.



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THE ORBIT AND SPECTRUM OF H. R. 8803

BY S. L. BOOTHROYD

The variable radial velocity of H. R. 8803 ($\alpha = 23^{\text{h}}. 03.0^{\text{m}}; \delta = +59^{\circ} 13'$) was discovered by Dr. J. S. Plaskett from five spectograms obtained at the Dominion Astrophysical Observatory at Victoria, B.C., between the dates August 22 and September 15, 1918. The binary character of the star was announced by Dr. Plaskett in the Journal of the Royal Astronomical Society of Canada for November, 1918. The writer secured eleven more spectograms between August 14 and September 22, 1919, while at the Dominion Astrophysical Observatory during the summer of 1919. Thirteen more were secured by the writer and the members of the staff between August 4 and October 18, 1920. The detailed results of the measurements are given in Table I. All the spectograms were measured by the writer with the exception of the first five, for which the measures made by Dr. Plaskett were used.

The spectrum is of type B3 with lines which are often faint or else rather diffuse, but, on the whole, not what might be regarded as difficult to measure. On plates 486, 617, 2811 and 2931 from two to three very weak lines of the secondary spectrum could be seen and these were measured, with results as indicated in the foot notes to Table I. These measures of the secondary were not included in the least-squares adjustment because they are so few and because being such very faint and difficult lines, their inclusion would not strengthen the solution. From the plotted positions of the observations for the secondary on the diagram of the velocity curves, as derived from the final elements, the mass of the secondary is judged to be about four-fifths of the mass of the primary.

In Table I the phases are reckoned from the final value of periastron passage using the corrected period of 7.25050 days.

From the preliminary elements (see Table IV), observation equations were built up according to the notation of Lehman-Filhés and a least-squares solution effected. Since the observations extended over parts of three seasons, the period was also included in the solution, which necessitated treating all the observations separately.

By making the following transformations, a set of 29 observation equations (given in Table 2) involving the six unknowns γ , K , e , P , ω and T were built up. The weights of each are as given in the second column.

$$\begin{aligned} x &= \delta \gamma \\ y &= \delta K \\ z &= 100 \delta e \\ u &= \frac{200 \pi K}{P^2 (1-e^2)^{\frac{3}{2}}} \delta P = -[3.16421] \delta P \\ v &= 100 \delta \omega \\ w &= \frac{2 \pi K}{P (1-e^2)^{\frac{3}{2}}} \delta T = [2.02455] \delta T \end{aligned}$$

From these observation equations, the normal equations given in Table III were formed.

TABLE II
OBSERVATION EQUATIONS FOR H. R. 8803

1	3	1.000x	-0.085y	+0.118z	-1.344u	+0.560v	-0.355w	+2.100=0
2	1	1.000	+0.312	-0.574	-1.569	+0.556	-0.406	+6.200
3	2	1.000	+0.816	-0.988	-1.742	+0.297	-0.452	-2.600
4	1	1.000	+0.406	-0.712	-1.529	+0.533	-0.419	+9.200
5	2	1.000	+0.907	-0.906	-1.578	+0.197	-0.434	-4.100
6	1	1.000	+0.721	-0.996	-0.139	+0.377	-0.454	-3.500
7	3	1.000	-0.296	+0.489	-0.086	+0.498	-0.334	-0.700
8	1	1.000	+0.087	-0.194	-0.093	+0.577	-0.375	+7.300
9	2	1.000	+0.132	-0.274	-0.094	+0.577	-0.381	-4.800
10	1	1.000	+0.583	-0.915	-0.105	+0.463	-0.443	-6.600
11	1	1.000	+1.058	-0.423	-0.066	-0.080	-0.291	-5.300
12	2	1.000	+0.676	-0.980	-0.008	+0.408	-0.453	+5.000
13	1	1.000	+0.015	-0.667	-0.003	-1.299	+1.886	+5.800
14	1	1.000	-0.327	+0.567	+0.011	+0.486	-0.333	-5.300
15	$\frac{1}{2}$	1.000	+0.083	-0.185	+0.016	+0.577	-0.375	+8.900
16	1	1.000	+1.010	-0.656	+0.023	+0.035	-0.366	+2.900
17	3	1.000	+1.068	-0.353	+0.863	-0.112	-0.265	-0.100
18	3	1.000	+0.181	-0.247	-6.313	-1.300	+1.935	-2.200
19	3	1.000	-0.373	+0.614	+1.080	+0.463	-0.328	+1.100
20	2	1.000	+0.036	-0.102	+1.218	+0.575	-0.369	-2.200
21	3	1.000	+0.946	-0.838	+1.384	+0.145	-0.416	+1.200
22	1	1.000	+1.070	+0.792	-1.258	-0.604	+0.370	+7.600
23	2	1.000	+0.974	+1.140	-2.745	-0.825	+0.807	+4.800
24	$\frac{1}{2}$	1.000	-0.596	-1.273	-3.534	-1.034	+1.036	-10.800
25	2	1.000	-0.663	+0.934	+1.017	+0.240	-0.291	+1.300
26	3	1.000	+0.528	+0.667	-6.250	-1.214	+1.760	+1.400
27	3	1.000	-0.753	+0.929	+0.933	+0.121	-0.261	-0.600
28	2	1.000	-0.703	+0.942	+0.999	+0.193	-0.280	+2.600
29	2	1.000	-0.889	+0.468	+0.339	-0.253	-0.085	-3.500

TABLE III
NORMAL EQUATIONS

+17.667x	+3.632y	+0.033z	-13.623u	+ 0.372v	+ 0.278w	+5.649=0
	+7.809	-4.500	- 8.502	- 1.223	+ 0.668	+6.322
		+ 8.753	- 0.255	- 1.138	+ 1.687	+8.660
			+100.782	+17.593	-25.575	-1.011
				+ 6.612	- 7.804	-0.555
					+10.472	+2.659

The solution of these equations gave corrections to the preliminary elements, as given in Table IV.

Since the final ephemeris residuals agreed closely with those obtained by substitution in the observation equations, it was unnecessary to make more than one solution. The sum of the weighted squares of the residuals is reduced from 771 to 622, or nearly 20 per cent.

TABLE IV
TABLE OF ELEMENTS

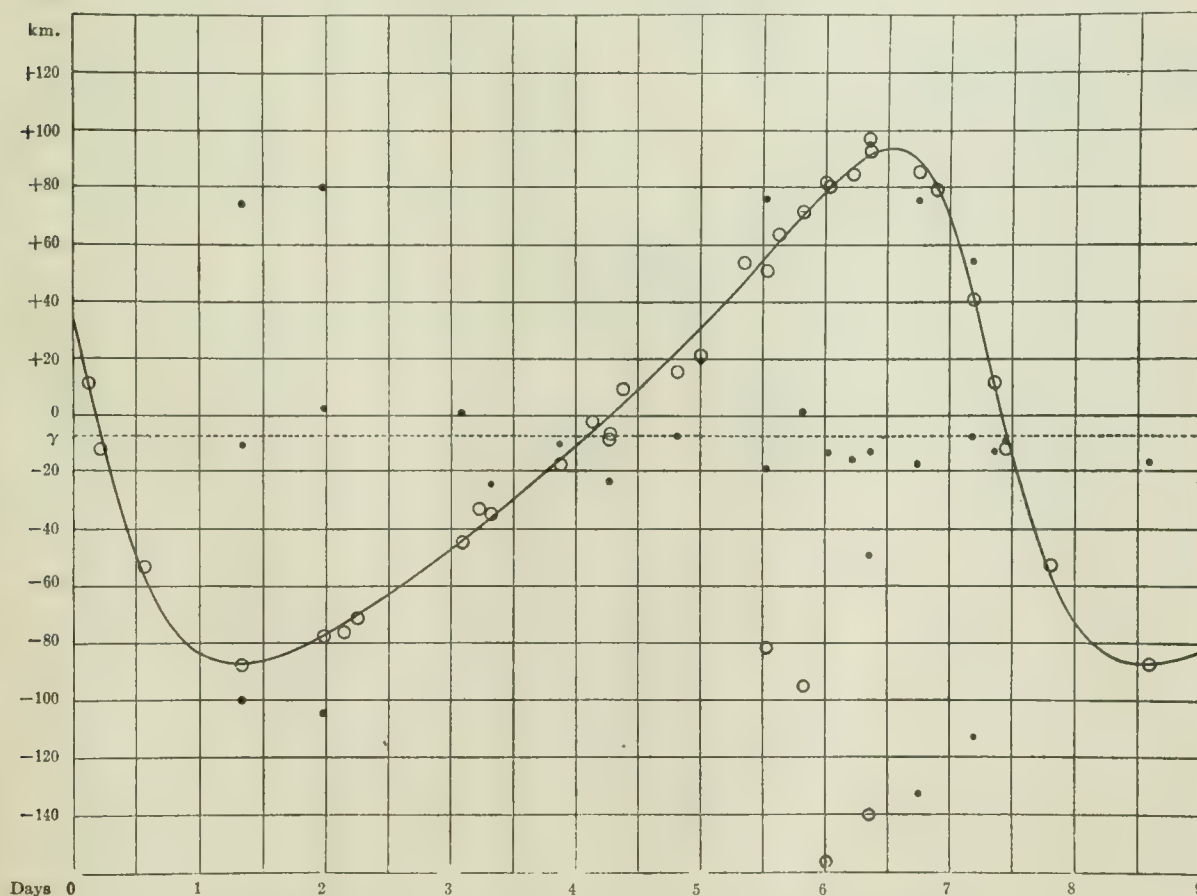
Element		Preliminary	Final
Period.....	P	7.250 days	7.25050 \pm 0.00008 days
Eccentricity.....	e	0.40	0.376 \pm 0.005
Longitude of apse.....	w	75°	71°.58 \pm 2°.66
Velocity of system.....	γ	-7.50 km. per sec.	-7.45 \pm 0.02 km. per sec.
Semi-amplitude.....	K	94.0 km.	90.54 \pm 0.78 km.
Periastron passage.....	T	J. D. 2,421,825.120	J. D. 2,421,825.038 \pm 0.044 days
Semi-major axis.....	$a \sin i$		7,751,000 km.
Mass	$(m_1+m_2 \sin^3 i)$		0.3464 \odot

A general idea of the precision of the measures may be obtained from an inspection of the radial velocity curve. The points indicated by open circles are individual observations obtained by averaging the velocities obtained from the measures of all lines, except the calcium lines, the number of lines used for each plate being indicated in the seventh column of Table 1. The probable error of a single observation is ± 2.60 km.

The Calcium Lines.

Of the 29 spectograms secured for this star, fifteen of them show the K-line of calcium, and of these plate No. 4786 also showed the H-line with sufficient clearness to make it possible to get a measure with reasonable certainty that it was not a blend with H_c. Plates 2811 and 2931 also show a second component for the K-line which gives evidence of being an oscillating K-line belonging to the principal components and numbers 4902, 5029, 5040 and 5220 show two components, one being on each side of the

stationary component. These lines are always narrow, and while the stationary line is sometimes quite easy to measure, it is generally faint and the components are always faint. It is possible that a fault on the plate may have been measured in some cases instead of a line, or at least that the measures of a line may have been influenced by a fault near the line, but such cases must be rare, if indeed it occurs at all. The measures of one of these oscillating lines agree as well as can be expected, for a weak, faint line, with the velocity curve for the principal component, and the other seems to be the K-line for the secondary component, at least measures of it agree as well as one could expect, for a weak, faint line, with the probable velocity curve for the secondary component. This line is, if anything, the weakest of the three. The individual observations for the calcium lines are shown by small black dots on the diagram of the velocity curve. For the stationary line, the average velocity, -10.34 km., agrees fairly well with the velocity of the system, this mean being the mean of all the lines listed as stationary in Table 1, with the exception of the one giving a velocity of -49.6 . It is hard to explain this measure, unless a nearby fault influenced the result. At any rate, it was thought best not to include this observation in the mean.



Radial Velocity Curve for H. R. 8803. Showing Individual Observations.

○ Observed Velocities for all Lines used except Calcium, for Principal and Secondary Component.

● K-Line of Calcium, Observed Velocities.

So far as is known to the writer, the only other star which shows an oscillating K-line as well as the stationary K-line is σ Aquilæ¹. In the case of β Scorpii² and VV Orionis³ the one K-line visible oscillates but the amplitude of the oscillation is not so great as for the other lines.

This star seems to add another one to those which show oscillating K-lines as well as a stationary one and is especially interesting because the oscillating line for both primary and secondary component show on at least four plates; the only other case of this of which the writer is aware being on plate No. 2099 listed by Jordan in Table 73 on page 195 of Vol. 3 of the Publications of the Allegheny Observatory.

It is hoped that it will be possible to follow this very interesting star every few years to see if any systematic changes take place in the elements of its orbit and also to see if any changes occur in the character of the K-line.

I wish here again to express my appreciation of the kindness shown me by Dr. Plaskett and all the members of the staff of the Dominion Astrophysical Observatory for the assistance given me in prosecuting the work on this binary.

University of Washington,

Seattle, Wash.,

Feb. 1, 1921.

¹ Publications of the Allegheny Observatory 3, 189, 1916.

² " " " 2, 138, 1912.

³ " " " 3, 186, 1915.



PUBLICATIONS
OF THE
Dominion Astrophysical Observatory
VICTORIA
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EIGHTY-EIGHT SPECTROSCOPIC BINARIES

BY J. S. PLASKETT, W. E. HARPER, R. K. YOUNG, H. H. PLASKETT

The following list of 88 spectroscopic binaries discovered at this observatory is supplementary to the first 100 announced in Vol. I, No. 10 of these publications. These binaries have been discovered in the course of the regular radial velocity work of the observatory, which consisted in the observation of 772 stars from Boss's Preliminary General Catalogue. The radial velocities of 594 stars are now being published in Vol. II, No. 1 of these publications and this list of 88 and the preceding list of 100 binaries include all the binaries in the stars observed from the Boss Catalogue and a few additional stars observed before the main programme was decided upon.

The telescope and spectrograph with which these observations are being made has been fully described in Vol. I, No. 1 of these publications and only a short summary of the optical constants need be repeated here. The telescope has an effective aperture of 72 inches (182.9 cm.) the focal length of the principal mirror being 361.3 inches (903.3 cm.). The spectrograph is used with the Cassegrain combination, whose equivalent focal length is 108 feet (32.92 metres). A hole in the centre of the main mirror enables the spectrograph to be attached at the bottom of the telescope tube along the optical axis of the telescope, a very convenient position. The spectrograph which is arranged for either one, two or three prisms has been used with one prism only. Owing to war conditions, material for the three prisms ordered from the Brashear Co. could not be obtained and from May 7, 1918 to August 12, 1919, a 60° Hilger prism of flint glass 0.118, kindly loaned by Prof. Chant of the University of Toronto, was used. This was then replaced by the one now in use, a 62° prism of slightly denser glass also made by the Hilger Co., and of exquisite defining power. The collimator is of 2½ inches (63 mm.) aperture and 45 inches (1,143 mm.) focal length. Three cameras are provided of 3 inches (76 mm.) aperture and of 16.5 inches (419 mm.), 28 inches (711 mm.), and 38 inches (965 mm.) focal length respectively. With the first prism only the medium focus, 28 inch camera, giving a linear dispersion at H γ of nearly 35 Å per millimetre was used. With the new prism

the three cameras will give linear dispersions of 49, 29, and 22 Å per millimetre respectively. The medium focus camera is used for the major part of the stars, and only for those around the 8th magnitude or fainter will the short focus camera be required. As previously stated the instrument gives beautiful definition and the measures show very satisfactory accuracy.

Stars of the "early" types B and A are measured on micrometer microscopes, Toepfer and Gaertner being available. All stars of type between Fo and M are measured on the Hartmann Spectro-Comparator, unless, as occurs in a few cases, the lines are broad and diffuse when more reliable values can be obtained on the micrometer microscope. The probable error of a single plate measured on the spectro-comparator is frequently below one kilometre per second, while on the micrometer microscope it depends altogether upon the number and sharpness of the lines with a minimum value of one kilometre per second increasing to as much as five or six when the lines are few in number and very broad and difficult to set on.

As in all lists of spectroscopic binaries, a number of these have such a small range as to render the chances of obtaining a satisfactory orbit small, although there can be no doubt of the reality of the variation in velocity. The best that can be done with such stars is to obtain a sufficient number of well distributed spectra of each, say twelve, to enable the velocity of the system to be determined with satisfactory accuracy. For the binaries of larger range in which a fairly good orbit is possible, it is believed that sufficient plates should be secured to enable the elements to be determined.

To the end that the data given here may be sufficient to enable an intelligent selection of those suitable for investigation to be made by anyone, full information is given in the list of the date, measured velocity and quality of the plates. To this list are appended full notes giving the character of the spectrum and the suitability for measurement of each star.

In the table the first column gives the serial number of the binary beginning with 101, the second the Boss or Harvard numbers, the third the right ascension and declination for 1900. The fourth column gives the spectral type and visual magnitude and the fifth and sixth the date and Julian date of the observation. The seventh column gives the radial velocity, an asterisk indicating remeasurement; the eighth the quality of the individual plates as regards suitability of exposure and development, while the last column gives the initial of the discoverer, P standing for J. S. Plaskett, H for W. E. Harper, Y for R. K. Young and P' for H. H. Plaskett. The numbers of binaries discovered are for P 10, H 16, Y 24, P' 37.

All but one of these 88 binaries have been found in the course of the regular radial velocity program of Boss stars. The exception is the star H.R. 5992 investigated by Dr. J. W. Campbell, assistant during the summer vacation. Of the list of 100 binaries previously published, 86 were from the Boss star list. Then in Table III of Vol. II, No. 1 are 3 additional ones which makes a total of 176 binaries obtained during the main radial velocity program of Boss stars. From this program there resulted 537 stars of constant velocity which list forms the main table of the previously mentioned publication. Thus out of a total of 713 stars of all types 176, or one in every four, were found to be binary. Of these binaries one in every nine or nineteen in all showed both component spectra. An analysis of the numbers in each type may prove interesting.

Type	Investigated	Binaries	Percentage	Double Lines
Bo to B5 inclusive.....	24	11	46	
B8 and B9.....	49	24	49	
Ao.....	129	56	43	6
A2.....	56	22	39	5
A3 and A5.....	52	15	29	1
Fo.....	52	13	25	2
F2.....	30	3	10	
F5.....	36	11	31	3
F8.....	19	4	21	
Go.....	20	4	20	2
G5.....	52	2	4	
Ko.....	135	9	7	
K2 and K5.....	35	1	3	
Ma and Mb.....	24	1	4	

The percentage column shows the well known preference for the "early" classes. Ninety per cent are found in the types B, A and F and for the B's about every second star investigated proved to be binary. It is possible that a longer time interval or the use of higher dispersion might reveal as binaries some of those of the "later" types which are at present considered as constant in velocity.

No.	Star	R.A. 1900 Dec. 1900	Type Vis. Mag.	Date	Julian Day G.M.T.	Radial Velocity	Quality	Dis- cov- erer
101	Boss 37	00 ^h 10 ^m .6 +76° 24'	B9 6.23	1919 Aug. 20	2,422,191.975	+ 2	Good	P'
				Nov. 7	2,270.743	-11	"	
				1920 Aug. 7	2,544.955	-23*	Fair	
				Oct. 13	2,611.842	- 3	"	
				Nov. 7	2,636.746	- 9	Good	
				1921 Jan. 22	2,712.586	+18*	Fair	
102	Boss 76	00 ^h 20 ^m .7 +79° 30'	B9 6.53	1918 Oct. 8	2,421,875.774	+ 8.5	Good	P
				Oct. 19	1,886.823	- 1.0	"	
				Oct. 27	1,894.768	- 5.4	"	
				Oct. 29	1,896.765	+ 8.1	Fair	
				Nov. 26	1,924.660	+ 9.5	"	
				Nov. 26	1,924.676	-19.8	Good	
103	Boss 179	00 ^h 44 ^m .7 +63° 42'	F2 5.45	1918 Oct. 8	2,421,967.569	+ 1.8	Good	Y
				Aug. 10	2,181.973	+ 9.2	"	
				Sept. 7	2,209.886	+13.6	"	
				Sept. 16	2,218.870	+ 5.4	"	
				1920 Oct. 31	2,629.761	- 4.2	"	
104	Boss 201	00 ^h 50 ^m .8 +59° 50'	B9 5.54	1919 Jan. 8	2,421,967.583	-16.8	Good	Y
				Aug. 10	2,181.981	+23.4	"	
				Sept. 7	2,209.898	-12.0	"	
				Nov. 19	2,282.711	- 3.4	"	
				Dec. 7	2,300.890	-24.3	"	
105	Boss 216 Prec.	00 ^h 54 ^m .4 +44° 10'	B9 6.84	1918 Oct. 8	2,421,875.823	+24.8	Good	P
				Oct. 19	1,886.869	-11.0	"	
				Oct. 29	1,896.810	+ 4.0	"	
				1919 Jan. 7	1,966.665	- 6.1	"	
				Aug. 14	2,185.977	+36.5	Poor	
				1920 Oct. 25	2,623.858	+27.8	Good	
106	Boss 216 Foll.	00 ^h 54 ^m .4 +44° 10'	B9 6.04	1918 Oct. 8	2,421,875.808	+ 8.7	Good	P
				Oct. 19	1,886.858	+ 7.0	"	
				Oct. 29	1,896.823	-15.0	"	
				1919 Jan. 7	1,966.637	- 2.4	"	
				Jan. 7	1,966.649	+ 0.8	"	
				Aug. 14	2,185.966	+26.3	Fair	
188	Boss 234	00 ^h 59 ^m .8 +14° 24'	F2 5.65	1918 Oct. 8	2,422,185.990	+ 7.8	Good	P'
				Oct. 4	2,236.839	+12.7*	"	
				Oct. 26	2,258.820	+ 1.5	"	
				1920 Aug. 7	2,544.984	+ 1.6	"	
107	Boss 348	01 ^h 30 ^m .5 +16° 55'	A5 5.88	1919 Aug. 15	2,422,186.007	+ 9.2	Good	P'
				Oct. 29	2,261.816	- 1.1	"	
				1920 Aug. 21	2,558.998	+ 2.0	Poor	
				Sept. 5	2,573.890	+14.2	Fair	
				Oct. 18	2,616.857	-20.2	Good	

No.	Star	R.A. 1900 Dec. 1900	Type Vis. Mag.	Date	Julian Day G.M.T.	Radial Velocity	Quality	Dis- cov- erer
108	Boss 380	01 ^h 36 ^m .6 +60° 03'	B9 5.75	1918 Oct. 8	2,421,875.896	-39.3	Good	P
				Oct. 19	1,886.933	-41.0	"	
				Oct. 24	1,891.872	-43.6	Fair	
				Nov. 24	1,922.819	-47.3	Good	
				1919 Dec. 11	2,304.676	-51.1	"	
				Dec. 11	2,304.698	-48.8	"	
				1920 Sept. 2	2,570.965	-4.1	"	
				Sept. 2	2,570.975	-17.9	"	
109	Boss 403	01 ^h 42 ^m .8 +16° 27'	Ao 5.73	1918 Dec. 4	2,421,932.695	+6.0	Good	Y
				1919 Jan. 8	1,967.622	+3.3	"	
				Jan. 29	1,988.583	+3.9	"	
				Sept. 16	2,218.943	+14.1	"	
				1920 Sept. 29	2,597.883	+29.9	"	
				1921 Jan. 10	2,700.607	-2.0	"	
110	Boss 435	01 ^h 50 ^m .7 +01° 21'	Go 6.18	1920 Aug. 30	2,422,567.980	+36.9*	Fair	P'
				Oct. 13	2,611.924	+33.4*	"	
				Oct. 25	2,623.892	+30.0*	"	
				Dec. 13	2,672.769	+31.9	"	
				1921 Jan. 15	2,705.607	+21.7*	Poor	
				Feb. 16	2,737.634	+25.9*	"	
111	Boss 538	02 ^h 16 ^m .7 +41° 01'	B 7.7	1919 Aug. 29	2,422,200.968	-47.6	Good	Y
				Oct. 2	2,234.852	-32.2	"	
				Oct. 5	2,237.871	-66.8	"	
112	Boss 613	02 ^h 36 ^m .2 +67° 24'	A2 5.84	1918 Oct. 28	2,421,895.805	+58.4	Good	Y
				1919 Jan. 10	1,969.642	+57.1	"	
				Oct. 5	2,237.905	+34.3	"	
				Nov. 4	2,267.791	-32.0	Fair	
113	Boss 726	03 ^h 08 ^m .4 +84° 34'	Ko 5.78	1919 Oct. 6	2,422,238.930	+33.8	Good	H
				1920 Jan. 5	2,329.695	+38.1	"	
				Feb. 9	2,364.665	+38.7	"	
				Dec. 30	2,689.765	+28.5*	Fair	
				1921 April 7	2,787.923	+27.0	"	
				May 11	2,821.856	+28.6*	Good	
114	Boss 735	03 ^h 10 ^m .5 +69° 22'	Ao 6.68	1919 Oct. 17	2,422,249.915	-8.9	Good	P'
				Nov. 7	2,270.885	+1.0	"	
				Dec. 2	2,295.790	-4.5	"	
				1920 Oct. 13	2,611.958	-39.2	"	
115	Boss 863	03 ^h 40 ^m .3 +05° 44'	B3 5.36	1919 Sept. 8	2,422,210.034	+10.4	Good	Y
				1920 Sept. 4	2,572.019	+2.0	"	
				Sept. 29	2,597.950	-9.7	"	
				Oct. 31	2,629.864	-4.1	"	
				Nov. 4	2,633.856	+20.1	"	
				1921 Jan. 10	2,700.689	+34.8	"	
116	Boss 961	04 ^h 06 ^m .0 +05° 16'	Fo 5.71	1919 Jan. 31	2,421,990.641	+54.9	Good	Y
				Feb. 26	2,016.600	+21.4	"	
				Nov. 19	2,282.807	+33.4	"	
				1920 Feb. 8	2,363.598	+34.8	"	

No.	Star	R.A. 1900 Dec. 1900	Type Vis. Mag.	Date	Julian Day G.M.T.	Radial Velocity	Quality	Dis- cov- erer
117	Boss 971	04 ^h 08 ^m .2 +07° 28'	Fo 5.35	1919 Oct. 17	2,422,249.940	+ 4.4	Good	P'
				Oct. 29	2,261.913	+ 8.8	"	
				Nov. 29	2,292.809	-11.0	"	
				Dec. 30	2,323.756	- 7.2	"	
118	Boss 1191	04 ^h 56 ^m .3 +85° 50'	A5 6.54	1919 Oct. 17	2,422,249.972	-17.9	Fair	P'
				Dec. 2	2,295.838	-11.8	Good	
				1920 Oct. 13	2,611.986	-30.1	Fair	
				Dec. 13	2,672.804	+14.9	"	
				1921 Jan. 9	2,699.775	+ 7.5	"	
				Feb. 7	2,728.662	-14.8	"	
119	Boss 1219	05 ^h 02 ^m .5 +08° 22'	Fop 5.47	1918 Nov. 4	2,421,902.901	+ 0.2	Good	Y
				Dec. 30	1,958.787	+ 4.3	"	
				1919 Oct. 3	2,235.016	+ 4.9	Fair	
				Dec. 3	2,296.799	+13.8	Good	
				1920 Feb. 8	2,363.636	+ 8.2	"	
				1921 Jan. 10	2,700.738	+ 0.0	"	
120	Boss 1229	05 ^h 04 ^m .2 +62° 34'	A2 6.38	1919 Oct. 4	2,422,236.044	-16	Fair	H
				1920 Jan. 5	2,329.718	-19	"	
				Feb. 9	2,364.604	+22*	Good	
				Mar. 1	2,385.606	-32*	"	
				Nov. 5	2,634.891	+24	Fair	
				1921 Jan. 8	2,698.810	- 1	"	
121	Boss 1253	05 ^h 10 ^m .8 +58° 01'	B3 6.23	1919 Feb. 5	2,421,995.638	+ 8.5	Good	Y
				Feb. 17	2,007.658	+ 5.4	"	
				Dec. 7	2,300.783	- 4.1	"	
				1920 Oct. 28	2,626.973	-17.5	"	
				1921 Feb. 14	2,735.646	- 5.1	"	
122	Boss 1282	05 ^h 16 ^m .4 +08° 20'	B2 5.71	1918 Dec. 21	2,421,949.865	+18.1	Good	P
				Dec. 29	1,957.887	+20.4	"	
				1919 Jan. 7	1,966.834	+12.7	"	
				Jan. 19	1,978.794	+15.5	"	
				Dec. 4	2,297.883	+37.2*	"	
				1920 Oct. 12	2,610.042	+22.0	"	
123	Boss 1367	05 ^h 30 ^m .6 +56° 18'	F5 6.89	1919 Oct. 7	2,422,239.060	+33.0*	Fair	H
				1920 Jan. 5	2,329.754	+22.5	"	
				Jan. 21	2,345.648	+10.1	Good	
				Feb. 9	2,364.624	+10.6	"	
				Mar. 1	2,385.621	+23.9	"	
				Nov. 5	2,634.927	+22.1	Poor	
124	Boss 1431	05 ^h 42 ^m .4 +20° 50'	B9 5.94	1918 Nov. 20	2,421,918.925	+21.0	Poor	Y
				1919 Dec. 3	2,296.820	+39.6	"	
				1920 Feb. 25	2,380.641	+17.6	Fair	
				1921 Jan. 10	2,700.772	+11.2	Good	
				Feb. 20	2,741.660	- 5.6	"	
				April 13	2,793.662	-36.9	"	
125	Boss 1471	05 ^h 50 ^m .4 +67° 00'	Ao 6.87	1919 Nov. 7	2,422,270.966	- 13.0	Good	P'
				Dec. 2	2,295.873	- 33.6	Fair	
				1920 Oct. 19	2,617.048	- 14.0	Good	
				Dec. 13	2,672.820	- 8.6	"	

No.	Star	R.A. 1900 Dec. 1900	Type Vis. Mag.	Date	Julian Day G.M.T.	Radial Velocity	Quality	Dis- cov- erer
126	Boss 1518	06 ^h 00 ^m .7 +23° 39'	Ko 6.89	1919 Feb. 2	2,421,992.738	- 11.8	Good	P
				Mar. 8	2,026.666	- 10.7	"	
				Mar. 23	2,041.629	- 20.5*	Fair	
				1920 Dec. 13	2,672.844	- 14.5	"	
127	Boss 1649	06 ^h 26 ^m .4 +17° 51'	F8 6.72	1919 Dec. 30	2,422,323.880	+ 3.9	Fair	P'
				1920 Oct. 30	2,628.973	- 4.5	Poor	
				Dec. 11	2,670.923	+ 8.9*	"	
				1921 Feb. 16	2,737.665	- 7.2*	Fair	
				Feb. 25	2,746.614	- 14.1*	Poor	
128	Boss 1667	06 ^h 28 ^m .7 +19° 30'	Ao 6.88	1919 Dec. 1	2,422,294.915	+ 21	Fair	H
				Dec. 5	2,298.862	+103}	"	
						- 4}		
				1920 Feb. 13	2,368.702	+ 25	"	
				Feb. 27	2,382.666	+ 10	Good	
				1921 Feb. 15	2,736.747	+115}	"	
129	Boss 2085	07 ^h 48 ^m .4 +56° 46'	Ao 6.49	1919 Feb. 17	2,422,007.772	+ 38.2	Good	Y
				Mar. 19	2,037.686	+ 5.5	"	
				1920 Feb. 22	2,377.765	+ 34.7	"	
				Feb. 25	2,380.718	+ 39.9	"	
				Mar. 21	2,405.653	+ 22.3	"	
130	Boss 2112	07 ^h 54 ^m .5 +57° 33'	Go 6.52	1920 Feb. 13	2,422,368.770	+ 1.7	Good	H
				Feb. 23	2,378.708	+ 35.2	"	
				Mar. 15	2,399.703	+ 85.8}	Fair	
						- 32.6}		
				April 5	2,420.656	+ 89.2}	"	
131	Boss 2206	08 ^h 14 ^m .6 +24° 20'	Ao 5.87	1919 Jan. 7	2,421,966.936	+16.7*	Good	H
				Feb. 23	2,013.798	+26.2*	"	
				Mar. 18	2,036.778	+22.2	"	
				April 6	2,055.683	+12.6*	"	
				1920 Feb. 27	2,382.748	+10.6	"	
				1921 April 15	2,795.666	+22.5	"	
				April 29	2,809.676	+52.0*	Fair	
				May 11	2,821.691	+18.9	Good	
132	Boss 2311	08 ^h 34 ^m .7 +19° 54'	A2 6.38	1919 Jan. 6	2,421,965.921	+37.7	Fair	Y
				Mar. 21	2,039.724	+43.4	Good	
				1920 Feb. 8	2,297.003	+32.3	Fair	
				Feb. 29	2,384.748	-13.6}	Good	
133	Boss 2377	08 ^h 46 ^m .4 +32° 51'	A3 5.75	1918 Dec. 16	2,421,944.997	-12.7	Good	Y
				Dec. 30	1,958.922	-10.9	"	
				1919 Jan. 6	1,965.906	- 8.7	"	
				Mar. 24	2,042.723	-49.7	Fair	
				Dec. 4	2,297.031	-19.4	Good	
				1920 Feb. 25	2,380.756	- 5.0	"	

No.	Star	R.A. 1900 Dec. 1900	Type Vis. Mag.	Date	Julian Day G.M.T.	Radial Velocity	Quality	Dis- cov- erer
134	Boss 2383	08 ^h 48 ^m .1 +64° 59'	G5 5.62	1919 Mar. 19	2,422,037.713	+ 6.2	Good	Y
				April 14	2,063.666	+ 4.5	"	
				1920 Feb. 22	2,377.784	- 5.0	"	
				Feb. 29	2,384.760	- 3.8	"	
				Mar. 21	2,405.705	- 5.9	"	
				Mar. 24	2,408.677	- 8.4	"	
135	Boss 2415	08 ^h 54 ^m .5 +84° 35'	F0 6.26	1920 Feb. 13	2,422,368.790	-12	Good	H
				Mar. 1	2,385.733	-36	"	
						+70		
				Mar. 15	2,399.733	+15	Poor	
				April 9	2,424.697	+41	Good	
						-44		
136	Boss 2420	08 ^h 56 ^m .1 +17° 28'	B9 7.11	April 23	2,438.681	-17	Fair	P'
				1920 Feb. 24	2,422,379.818	- 8	Fair	
				1921 Feb. 16	2,737.917	+ 1*	Poor	
				Mar. 29	2,778.697	-22*	Fair	
				April 5	2,785.679	+ 2	"	
				April 8	2,788.676	+51*	"	
137	Boss 2462	09 ^h 06 ^m .3 +18° 27'	A0 6.75	May 3	2,813.720	+16	"	P'
				1920 Feb. 10	2,422,365.818	+26	Good	
				Feb. 28	2,383.806	+14	"	
				April 20	2,435.690	-25	Fair	
138	Boss 2522	09 ^h 18 ^m .5 +54° 27'	A2 7.36	1920 Feb. 21	2,422,376.841	+ 5*	Fair	P'
				1921 Feb. 16	2,737.952	+51*	Poor	
				Mar. 29	2,778.729	+16	Good	
				Mar. 29	2,778.761	+23	"	
				April 5	2,785.801	+26)*	Fair	
						-72		
139	Boss 2644	09 ^h 46 ^m .3 +38° 23'	F0 6.74	April 5	2,785.829	+42*	"	P
				1919 Mar. 18	2,422,036.854	+30.0*	Good	
				April 6	2,055.760	+ 1.6	Poor	
				1920 Dec. 14	2,673.065	+ 2.4	Good	
140	Boss 2678	09 ^h 54 ^m .5 +03° 52'	A5 6.63	1919 Dec. 3	2,422,296.068	- 8	Good	P'
				1920 Feb. 28	2,383.887	-15	"	
				1921 April 5	2,785.725	+23	Poor	
				April 5	2,785.743	+36*	"	
				April 8	2,788.740	-28*	"	
				May 12	2,822.753	-32	"	
141	Boss 2824	10 ^h 32 ^m .2 +34° 36'	K0 6.65	1920 Feb. 24	2,422,379.883	+11.9	Good	P'
				May 6	2,451.686	+12.5	Fair	
				1921 Mar. 29	2,778.899	+17.2	Good	
				April 5	2,785.887	+17.0	Poor	
				April 8	2,788.836	+20.3	"	
				May 3	2,813.755	+21.3	Good	

No.	Star	R.A. 1900 Dec. 1900	Type Vis. Mag.	Date	Julian Day G.M.T.	Radial Velocity	Quality	Dis- cov- erer
142	Boss 2874	10 ^h 42 ^m .1 +06° 52'	A2 7.01	1919 May 2	2,422,081.714	+52	Fair	H
				1920 April 9	2,424.737	+61	"	
						-46		
				April 12	2,427.738	+55	Poor	
				April 23	2,438.728	-25	"	
				April 30	2,445.701	+42	Fair	
				1921 April 27	2,807.687	-4	"	
143	Boss 2951	11 ^h 02 ^m .3 +23° 52'	A2 6.39	1918 May 13	2,421,727.687	-17.1	Poor	Y
				Dec. 31	1,959.002	-7.8	Good	
				1919 Jan. 6	1,965.962	-15.0	"	
				Mar. 21	2,039.817	-12.6	"	
				April 23	2,072.703	+7.5	"	
144	Boss 2953	11 ^h 02 ^m .5 +86° 11'	A2 7.17	1920 Feb. 10	2,422,365.903	-6.9	Good	P'
				Feb. 28	2,383.925	-1.4	"	
				1921 Mar. 29	2,778.830	+1.1	"	
				April 5	2,785.771	-15.2	Fair	
				April 21	2,801.751	+1.4*	"	
				May 3	2,813.684	-17.4*	Good	
145	Boss 3009	11 ^h 20 ^m .5 +03° 51'	A2 6.70	1920 Feb. 13	2,422,368.914	+18	Fair	H
				Feb. 27	2,382.888	+15	"	
				Mar. 1	2,385.885	+14	"	
				April 9	2,424.758	-0	"	
				1921 April 7	2,787.874	+20	Poor	
				April 15	2,795.835	+15	Fair	
				April 27	2,807.730	-16	"	
146	Boss 3011	11 ^h 20 ^m .7 +04° 25'	Fo 6.36	1920 Feb. 10	2,422,365.934	-18	Fair	P'
				Feb. 23	2,379.925	-16	"	
				April 24	2,439.760	+12	"	
				May 6	2,456.724	+1	"	
				May 23	2,468.703	-11	Good	
147	Boss 3180	12 ^h 06 ^m .7 +26° 25'	Ko 5.81	1920 Feb. 7	2,422,362.975	+7.6*	Fair	P'
				Feb. 21	2,376.917	+17.4*	Good	
				Mar. 16	2,400.857	+26.5	"	
				April 13	2,428.792	+33.1	"	
				April 20	2,435.772	+31.8	Fair	
148	Boss 3299	12 ^h 34 ^m .2 +21° 36'	Ko 5.51	1919 Mar. 21	2,422,039.884	-30.0	Good	Y
				April 14	2,063.793	-28.3	"	
				April 21	2,070.806	-26.2	"	
				1920 Feb. 8	2,363.988	-23.2	"	
				Feb. 25	2,380.934	-30.7	Poor	
				May 2	2,447.726	-18.4	Good	
149	Boss 3306	12 ^h 36 ^m .6 +10° 58'	A5 6.33	1919 Mar. 18	2,422,036.885	-2.4	Good	P
				May 3	2,082.758	-6.1	"	
				1920 April 13	2,428.822	+25.7	"	
				May 4	2,449.751	+31.6	Fair	
				June 10	2,486.747	+38.9	Poor	

No.	Star	R.A. 1900 Dec. 1900	Type Vis. Mag.	Date	Julian Day G.M.T.	Radial Velocity	Quality	Dis- cov- erer
150	Boss 3613	13 ^h 56 ^m .6 +27° 52'	A3 6.12	1919 Mar. 19	2,422,037.929	-18.9	Good	Y
				Mar. 28	2,046.919	-22.1	"	
				April 21	2,070.824	-41.6	"	
				May 19	2,098.685	-22.7	"	
				1920 Feb. 25	2,380.964	-19.3	"	
				May 2	2,447.801	-12.1	"	
151	Boss 3793 Foll.	14 ^h 46 ^m .3 +49° 07'	F5 5.64	1920 Feb. 22	2,422,377.026	+25.3	Good	P'
				Feb. 29	2,384.031	-36.0	"	
				April 24	2,439.871	+ 8.3	"	
152	Boss 4005	15 ^h 40 ^m .2 +17° 34'	A0 5.89	1919 Mar. 24	2,422,042.994	+17.2	Poor	Y
				Mar. 28	2,046.977	- 5.2	Good	
				April 14	2,063.941	- 1.3	Fair	
				June 1	2,111.798	-38.0	Good	
				1920 May 5	2,450.812	- 0.1	"	
				May 15	2,460.780	-21.0	Poor	
				June 2	2,478.746	+ 5.9	Good	
153	Boss 4056	15 ^h 52 ^m .2 +42° 51'	B8 5.61	1919 Mar. 18	2,422,036.997	- 3.4	Good	P
				May 6	2,085.839	-28.7	"	
				May 6	2,085.850	-14.6	"	
				June 26	2,136.766	-14.0	"	
				1920 Mar. 17	2,401.002	-34.9	"	
				Mar. 17	2,401.008	-29.0	"	
				June 10	2,486.806	- 3.5	"	
				June 10	2,486.831	- 3.2	"	
154	H.R. 5992	16 ^h 00 ^m .8 +08° 22'	A 6.1	1921 June 11	2,422,852.745	-35.1	Fair	C
				June 18	2,859.777	-19.7	"	
				June 22	2,863.715	-49.6	Good	
155	Boss 4129	16 ^h 08 ^m .1 +36° 41'	K5 5.68	1918 May 26	2,421,740.803	-34.2	Good	Y
				May 27	1,741.823	-31.7	"	
				June 2	1,747.830	-35.8	"	
				1919 May 4	2,083.897	-13.7	"	
				May 19	2,098.799	-10.5	"	
				June 17	2,127.813	- 9.4	"	
				1920 Feb. 23	2,378.083	-33.3	"	
156	Boss 4177	16 ^h 19 ^m .3 +07° 10'	A0 5.72	1918 June 27	2,421,772.719	-21.6	Good	Y
				July 12	1,787.744	-16.9	"	
				1919 Mar. 25	2,043.034	-31.2	Poor	
157	Boss 4260	16 ^h 40 ^m .4 +01° 12'	B9 5.99	June 1	2,111.825	-44.7	Good	P'
				1920 Feb. 11	2,422,366.114	- 8.6	Good	
				Feb. 25	2,380.082	-26.3	"	
				April 11	2,426.006	-12.2	"	
				May 14	2,459.870	-25.0	"	
158	Boss 4266	16 ^h 42 ^m .2 +02° 14'	A2 6.04	1920 Feb. 22	2,422,377.084	-13.4	Good	P'
				April 13	2,428.961	-29.6	"	
				June 1	2,477.838	-39.6	"	
						+30.7	"	

No.	Star	R.A. 1900 Dec. 1900	Type Vis. Mag.	Date	Julian Day G.M.T.	Radial Velocity	Quality	Dis- cov- erer
167	Boss 4765	18 ^h 44 ^m .5 +52° 53'	B5 5.76	1919 Aug. 24	2,422,195.702	+23.1	Good	P'
				1920 July 3	2,509.814	+15.3	"	
				July 24	2,530.800	-18.2	"	
168	Boss 4777	18 ^h 46 ^m .4 +33° 14'	B2p Var.	1920 June 19	2,422,495.892	-21.9	Good	P'
				July 6	2,512.827	-25.2	"	
				July 31	2,537.840	-17.0*	"	
				Aug. 7	2,544.818	+11.1*	Fair	
169	Boss 4798	18 ^h 50 ^m .6 +06° 30'	G5 5.66	1919 Aug. 7	2,422,178.758	+12.5*	Good	P'
				1920 July 24	2,530.810	+26.6	"	
				Aug. 3	2,540.825	+22.4	"	
				Sept. 2	2,570.685	+26.7	"	
170	Boss 4837	18 ^h 56 ^m .9 +75° 39'	Ao 6.18	1920 June 29	2,422,505.879	+ 0.5	Fair	P'
				July 26	2,532.805	+19.5*	Good	
				Aug. 10	2,547.781	-13.8	Fair	
				1921 Mar. 27	2,776.974	-11.7*	"	
171	Boss 4838	18 ^h 56 ^m .9 +75° 39'	Ao	1920 July 3	2,422,509.843	-20.6	Good	P'
				July 26	2,532.783	-23.5	Fair	
				Aug. 10	2,547.783	-30.2	"	
				1921 Mar. 27	2,776.992	-10.9	Good	
				Mar. 30	2,779.016	- 3.7	Fair	
				July 9	2,880.774	-20.7	Good	
172	Boss 4845	18 ^h 58 ^m .5 +01° 40'	A2 5.72	1919 July 18	2,422,158.853	+ 4*	Good	H
				Aug. 18	2,189.730	-17	"	
				1920 June 28	2,504.881	-32*	"	
				July 12	2,518.867	-39*	Fair	
				Sept. 28	2,596.619	-36	Good	
				Nov. 9	2,638.555	-36	Fair	
				1921 May 20	2,830.929	-76) +70)	Good	
173	Boss 4951	19 ^h 20 ^m .2 +16° 46'	Ao 6.76	1920 July 6	2,422,512.859	-28.4	Fair	P'
				July 24	2,530.834	+ 7.6	"	
174	Boss 4971	19 ^h 22 ^m .5 +88° 59'	Mb 6.55	1919 July 13	2,422,153.840	- 0.7	Good	Y
				Aug. 10	2,181.755	- 7.6	Poor	
				Aug. 29	2,200.683	- 1.0	"	
				1920 June 20	2,496.884	+ 3.6	"	
				July 14	2,520.821	+ 6.8	"	
175	Boss 4981	19 ^h 25 ^m .0 +20° 04'	B3 6.39	Sept. 3	2,571.685	+ 2.6	Good	
				1919 Aug. 14	2,422,185.790	+17.8	Fair	P'
				Oct. 17	2,249.597	+ 2.4	Good	
				1920 July 31	2,537.870	-15.0	Fair	
176	Boss 5123	19 ^h 54 ^m .8 +22° 50'	Fo 5.70	Aug. 12	2,549.790	-11.6	"	H
				1919 July 3	2,422,143.852	-30	Good	
				Sept. 1	2,203.751	-40	Fair	
				Sept. 9	2,211.705	-46	Good	
				1920 June 28	2,504.898	-77	"	
				Oct. 26	2,624.596	-38	Fair	
				Oct. 29	2,627.630	-20	Good	
				Nov. 9	2,638.591	-24	"	

No.	Star	R.A. 1900 Dec. 1900	Type Vis. Mag.	Date	Julian Day G.M.T.	Radial Velocity	Quality	Dis- cov- erer
177	Boss 5126	19 ^h 56 ^m .2 +45° 30'	A2 5.80	1919 Oct. 17	2,422,249.618	-11.4	Good	P'
				1920 July 6	2,512.873	+1.4	"	
				July 31	2,537.885	-1.1	"	
				Aug. 21	2,558.769	-10.2	Fair	
				Sept. 16	2,584.788	+21.7	Good	
178	Boss 5230	20 ^h 18 ^m .9 +45° 27'	Ko 5.87	1919 July 22	2,422,162.857	-18.5*	Good	P'
				Nov. 7	2,270.589	-21.4	"	
				1920 July 25	2,531.810	-28.8*	"	
				Oct. 27	2,625.708	-25.9	"	
179	Boss 5289	20 ^h 32 ^m .8 +26° 07'	B9 5.52	1919 Aug. 14	2,422,185.842	+21*	Good	P'
				Oct. 17	2,249.634	-8*	"	
				1920 Sept. 27	2,595.808	-34*	"	
				Oct. 9	2,607.680	-22	Fair	
180	Boss 5384	20 ^h 50 ^m .9 +12° 12'	A2 5.54	1919 Aug. 14	2,422,185.876	-10.2	Good	P'
				1920 July 24	2,530.870	-6.6	"	
				Aug. 14	2,551.834	-12.5	"	
				Oct. 9	2,607.741	+15.4	Fair	
				Oct. 27	2,625.787	-10.8	"	
				1921 May 27	2,837.928	+18.3*	"	
181	Boss 5495	21 ^h 18 ^m .5 +48° 58'	Ko 5.87	1919 July 22	2,422,162.910	-1.0	Good	P'
				Oct. 23	2,255.673	-4.0	"	
				1920 Aug. 30	2,567.803	-4.3	"	
				Oct. 11	2,609.756	-8.6*	"	
				Dec. 4	2,663.577	+1.5*	Fair	
				Dec. 13	2,672.570	-3.2	"	
182	Boss 5528	21 ^h 26 ^m .5 +52° 30'	Ao 7.17	1919 Sept. 21	2,422,223.758	-40	Good	H
				Oct. 6	2,238.705	-24	"	
				Nov. 7	2,287.575	-7	Poor	
				1920 Oct. 6	2,624.737	+28	Good	
				1921 July 11	2,882.798	-12	"	
183	Boss 5536	21 ^h 28 ^m .9 +75° 58'	Fo 7.67	1919 July 19	2,422,159.921	-67.6	Good	P
				Oct. 14	2,246.680	+49.4	Poor	
				1920 Sept. 2	5,570.822	-6.4	Fair	
184	Boss 5552	21 ^h 32 ^m .7 +06° 10'	Ao 6.05	1919 July 7	2,422,147.949	-6.9	Good	H
				July 14	2,154.917	+8.7	Poor	
				Aug. 21	2,192.829	+26.0	Fair	
				Sept. 18	2,220.787	+8.6	Good	
				1920 June 28	2,504.952	+5.5	"	
				1921 July 11	2,882.937	+16.3	"	
185	Boss 5700	22 ^h 04 ^m .7 +47° 27'	Ao 6.83	1919 Aug. 12	2,422,183.848	-20.7*	Fair	P'
				Oct. 17	2,249.679	-10.7*	Good	
				1920 Aug. 1	2,538.952	+7.6*	"	
				Aug. 30	2,567.821	-5.5*	"	
186	Boss 5771	22 ^h 18 ^m .8 +66° 12'	A2 7.3	1919 Sept. 7	2,422,209.836	-28.9	Fair	Y
				Sept. 24	2,226.727	-23.1	"	
				Oct. 5	2,237.725	+21.5	Good	

No.	Star	R.A. 1900 Dec. 1900	Type Vis. Mag.	Date	Julian Day G.M.T.	Radial Velocity	Quality	Dis- cov- erer
187	Boss 5936	22 ^h 58 ^m .0 +42° 13'	A2 5.08	1919 July 22	2,422,162.964	-32.0	Good	P'
				Oct. 4	2,236.797	-21.1	"	
				Oct. 15	2,247.741	-30.5	"	
				Oct. 29	2,261.735	- 6.9	"	
				1920 Aug. 10	2,547.912	+ 0.1	"	

NOTES

- No. 101—Boss 37—Characterized by broad hydrogen lines only with, on two plates, a trace of 4481. Re-measures are consistent.
- No. 102—Boss 76—The lines in this B9 star are broad and poorly defined. The hydrogen series and very weak helium are practically all that are measurable.
- No. 103—Boss 179—This is a sharp line F-type spectrum. The range of 18 km. is not very large for one prism but the plates upon which the greatest range occurs are very good and there can be little doubt of the binary character.
- No. 104—Boss 201—The K line of calcium, 4481 of magnesium and the hydrogen lines were all that were measured on the plates of this star. The lines vary in character somewhat, being quite sharp and narrow on the plate of Nov. 19 but rather diffuse on the others. On the plate of Dec. 7, K is certainly double, giving velocities -123 and +28 km.
- No. 105—Boss 216 Prec.—The lines are very broad and only the hydrogen series and 4481 measurable. Spectrum peculiar in having broad and strong K.
- No. 106—Boss 216 Foll.—The spectrum is very similar to the preceding star except that the K line is faint. The measures of both stars are uncertain owing to the character of the lines but there seems no doubt of their binary character. They are separated by about 8" and have common proper motion. The similarity of spectra, velocity and proper motion indicates physical connection.
- No. 188—Boss 234—Typical sharp line F2 spectrum. The first three plates were measured on the Toepfer machine and the last plate and the remeasure of the October 4th plate were made on the spectro-comparator. Though range is small, the star is probably a binary.
- No. 107—Boss 348—Numerous rather diffuse, though not very wide, lines characterize this spectrum.
- No. 108—Boss 380—This spectrum contains practically only the hydrogen lines measurable and they are broad but strong. The period appears to be long.

- No. 109—Boss 403—The lines in this spectrum, though not very numerous, are very sharp and narrow. K is a very good line. 4128 and 4131 are present and sharp. 4481 and 4549 are also sharp. The hydrogen series is strong and wide. $H\gamma$ has a well defined core.
- No. 110—Boss 435—This star is the double $\Sigma 186$, separation in 1904 $0''.66$. It has not been separated here. Plates are all under-exposed. Remeasures are, however, accordant and there can be little doubt that the star is a binary. The last two plates are the means of three measures each, two by P' and one by P .
- No. 111—Boss 538—The lines in this spectrum are faint but fairly well defined. K is a good line. The helium and hydrogen lines are only fair. Some oxygen lines are present and also the Pickering series of hydrogen. The K line gives a constant velocity of about -20 km.
- No. 112—Boss 613—Fine spectrum for measurement with the usual numerous enhanced iron lines so often seen in the spectrum of A2-type stars. The large range makes it a favourable star for having its orbit readily determined.
- No. 113—Boss 726—The range found is not large but the plates are good and remeasures are accordant so that there seems no doubt of the binary character of the star.
- No. 114—Boss 735—Broad hydrogen lines and good K, 4481 and 4534.
- No. 115—Boss 863—The lines in this spectrum are rather poor, from four to eight lines were measured. These consisted of the helium series and usual $H\delta$ and $H\gamma$. On the last plate a component is visible for two of the lines, displacement -100 km.
- No. 116—Boss 961—Good Fo-type spectrum and the measures, all of which were made on the Hartmann Comparator, should be reliable.
- No. 117—Boss 971—Lines too diffuse to measure on comparator, but very consistent results obtained on Toepfer.
- No. 118—Boss 1191—This star which was originally listed Ao is actually more nearly Fo. It has been measured on the comparator against Procyon. The range is large and the star should be suitable for further investigation.
- No. 119—Boss 1219—Fine spectrum. The small range would make the determination of an orbit difficult but it is felt that the range indicated is real as the plates are of very good quality.
- No. 120—Boss 1229—Hydrogen lines and calcium K are all very broad. If the spectrum is not too dense $\lambda 4481$ can also be measured. There are some suspicions of complexity particularly to the K-line on the plate of Nov. 5. Unless a greater range were found it would be difficult to get an orbit.
- No. 121—Boss 1253—The binary character of this star was decided chiefly from the presence of the secondary component. On the third plate there seems to be a line at $+99$ though this is not very certain. The last plate has a component at -204 km.

- No. 122—Boss 1282—The lines in this B2 spectrum are fairly sharp and the values accordant. Although the binary character depends on one plate, it seems to be unmistakable.
- No. 123—Boss 1367—Most of the measures are on the comparator. The first plate was checked on the micrometer with 1 km. difference in the result. The first, third and fourth plates are good and there seems no doubt of the binary character of the star.
- No. 124—Boss 1431—This is a very poor spectrum. Only the K line and poor wide hydrogen being used. The range obtained of 75 km. however, makes it practically certain that the star is a binary.
- No. 125—Boss 1471—This star is about A3 in type, rather than Ao. Lines are diffuse but measures are accordant.
- No. 126—Boss 1518—A K-type spectrum with sharp lines measured on the comparator makes the binary character of this star certain, although range is small.
- No. 127—Boss 1649—This is the preceding component of the double $\Sigma 924$. The following star has a constant velocity of -0.5 km.
- No. 128—Boss 1667—Two plates show double lines but they are poor for measurement. The plate of Feb. 27 shows the lines at their best and $\lambda 4481$ is fairly sharp so that this velocity is probably close to that of the system.
- No. 129—Boss 2085—The lines in the spectrum are fair. K is present and fairly sharp, $\lambda 4481$ is also good but faint. $\lambda 4549$ is present and there are traces of $\lambda 4227$, $\lambda 4233$, $\lambda 4534$ and other enhanced iron lines.
- No. 130—Boss 2112—The first two plates were measured on the comparator and the agreement among the regions themselves was not of the best. Plates three and four suggest the reason for this in the complexity of the spectrum.
- No. 131—Boss 2206—The hydrogen lines are broad but with good exposure narrow sufficiently to get fairly reliable results. On the deciding plates the magnesium line $\lambda 4481$ is good and shows an even greater range than here listed.
- No. 132—Boss 2311—The binary character of this star rests entirely on the last plate which shows a double spectrum. The stronger component is toward the red. There are many lines in the spectrum but they are only of fair quality for measurement.
- No. 133—Boss 2377—Numerous lines which are of fairly good quality are present in this star.
- No. 134—Boss 2383—Like so many of the late type binaries this star exhibits a small range. The slow change of the velocities indicates a long period.
- No. 135—Boss 2415—This spectrum has numerous lines quite fuzzy in character though this may be due to the partial superposition of the spectra on our plates. There seems no doubt that the two cases where the lines were measured as double are real.

- No. 136—Boss 2420—A star almost identical in spectrum with Boss 37. Exceedingly broad hydrogen lines with 4481 scarcely perceptible. 4549 also measured on one or two plates.
- No. 137—Boss 2462—Usual broad hydrogen lines and diffuse 4227, 4481, 4549.
- No. 138—Boss 2522—Broad hydrogen lines and a trace of 4481. The first spectrum secured on April 5, 1921 is probably double as components of lines can be measured giving velocities +26, -72.
- No. 139—Boss 2644—This Fo spectrum has very diffuse lines and was consequently measured on the micrometer microscope. Remeasure of the first plate gave practically the same velocity so there is no doubt of the binary character.
- No. 140—Boss 2678—Diffuse lines, difficult to measure. Plates tend to be under-exposed.
- No. 141—Boss 2824—Though the range is small, there can be little doubt of the binary character of this sharp line K.
- No. 142—Boss 2874—Fuzzy, ill-defined lines feature this spectrum but on the second plate the line $\lambda 4481$ is definitely double.
- No. 143—Boss 2951—Numerous lines are present in the spectrum. They are narrow but rather faint. The binary character rests almost entirely on the last plate.
- No. 144—Boss 2953—Type slightly more advanced than A2. Spectrum is characterized by many sharp lines.
- No. 145—Boss 3009—The magnesium line $\lambda 4481$ is the most dependable line on the plates though $H\gamma$ is passable at times and range shown is more than can be ascribed to accidental error of measurement.
- No. 146—Boss 3011—A typical fuzzy lined F, difficult to measure.
- No. 147—Boss 3180—This would probably be an interesting system to investigate as the range is quite good and period long. May be quite massive.
- No. 148—Boss 3299—This is a fine K-type spectrum and the range indicated is probably real. All the plates except the fifth are of very good quality.
- No. 149—Boss 3306—Broad hydrogen and K and weak magnesium make the measures somewhat uncertain.
- No. 150—Boss 3613—The binary character of this star seems fairly well established but the determination of orbital elements would be rather difficult. There are numerous lines in the spectrum. They are rather fuzzy and give rather discordant results.
- No. 151—Boss 3793 Foll.—This is the following star of the pair $\Sigma 1890$, separation $3''.5$. Both stars have a common proper motion. The preceding has a constant velocity of -32.3 km. The first plate on Feb. 22 shows in the violet beautiful, sharp, double lines with a separation of about 70 km. The plate was measured from $H\gamma$ — red and there this doubling was not visible, the lines appearing fuzzy. The doubling was only observed on looking over the plate preparatory to writing this note.

- No. 152—Boss 4005—The calcium line K is fair in the spectrum of this star, 4481 and 4549 are present but rather poor. Hydrogen lines are wide and strong.
- No. 153—Boss 4056—Broad and diffuse hydrogen and broad, faint magnesium are the only lines measurable in this spectrum.
- No. 154—H.R. 5992—Spectrum consists of numerous sharp lines. An orbit has since been determined and will appear shortly in these publications.
- No. 155—Boss 4129—The usual good lines of a K-type star characterize this spectrum. It has been under investigation here for some time but as yet no period has been discovered.
- No. 156—Boss 4177—The lines in this star are fairly good and numerous. K, H δ , H γ , 4481 and 4549 are the best. The two silicon lines 4128 and 4131 are present and also many faint, enhanced iron lines.
- No. 157—Boss 4260—Hydrogen lines well defined, 4481 strong and sharp. Measures are consistent and there can be little doubt of the binary character of this star.
- No. 158—Boss 4266—Diffuse line star. The measures of the third plate seem to indicate doubling and they are so represented in the table.
- No. 159—Boss 4351—The usual lines of a K-type star are present. All the plates are of very good quality.
- No. 160—Boss 4357—Two or three lines are measured on each plate and though poor, should warrant the conclusion that the star is a binary.
- No. 161—Boss 4401—The lines in the spectrum are exceedingly sharp and narrow. The range is small but there should be no particular difficulty in getting the period.
- No. 162—Boss 4437—The plates were measured on the comparator against the sky standard and from the range obtained there is no doubt of the binary character.
- No. 163—Boss 4516—Good spectrum and re-measures consistent. Though range is small, there can be little doubt of binary character.
- No. 164—Boss 4563—This star which is listed B8 is earlier, probably nearer B3. Lines are very diffuse.
- No. 165—Boss 4744—This is the double star $\Sigma 2375$, separation $1''.9$. Was not observed as double on the slit. Lines are very diffuse. Comparison weak in last plate.
- No. 166—Boss 4745—This star has an excellent spectrum to measure, the hydrogen lines being sharp and $\lambda\lambda 4481$ and 3933 exceedingly so. The last plate was taken on a night hardly deemed suitable to continue working yet the plate was most opportune as the star was caught "off guard" with its more refrangible lines beautifully resolved. An orbit will be attempted here.
- No. 167—Boss 4765—Star is more nearly B3. In second plate K line has a velocity of -4 km.

- No. 168—Boss 4777—This star is a faint, variable companion, $46''$, 149° of β Lyrae. Spectrum is listed B2p. From the strength of 4481 and of the hydrogen lines it is more nearly B8.
- No. 169—Boss 4798—Though range is small, star is probably a binary as measures on the comparator are very accordant.
- No. 170—Boss 4837—This and the following star form the pair $\Sigma 2452$. If the visual pair is a physical system, we have here an interesting quadruple system. This is a typical A0 spectrum.
- No. 171—Boss 4838—This is the other star of the pair $\Sigma 2452$. Spectra of the two stars practically identical.
- No. 172—Boss 4845—If it were not for the last plate, which has double lines, one would be likely to ascribe the variation found in the preceding plates to accidental error of measurement as only three or four lines on the average were measured.
- No. 173—Boss 4951—Probably more advanced than A0 as there are a number of good metallic lines.
- No. 174—Boss 4971—The binary character of this star rests upon the variation of the mean velocities for 1919 and the mean of those for 1920. The plates are a little weak but the lines are sharp and strong and the plates lend themselves to accurate measurement on the Hartmann Comparator.
- No. 175—Boss 4981—Type more nearly B5. Helium lines very diffuse.
- No. 176—Boss 5123—There are numerous ill-defined lines in this spectrum, about a dozen being measured. The plate of June 28 shows a positive component with velocity $+54$ but the violet is the stronger. A velocity of -33 km. would be near to that of the system.
- No. 177—Boss 5126—Spectrum is characterized by a great number of sharp metallic lines. Though range is not very large, yet it would probably make a suitable star for orbit determination.
- No. 178—Boss 5230—Beautiful spectrum to measure. Though range is small, star is probably a binary.
- No. 179—Boss 5289—Characterized by broad hydrogen lines, difficult to see any other lines. Very similar to Boss 37 and Boss 2420.
- No. 180—Boss 5384—Lines somewhat diffuse but measures on the whole are accordant.
- No. 181—Boss 5495—This star is just on the border line of being arbitrarily taken as a constant velocity. The re-measures were so consistent, however, that it has been included as a binary.
- No. 182—Boss 5528—There is some uncertainty but there seems to be good grounds for regarding the complex nature of the spectrum as real.

- No. 183—Boss 5536—This faint Fo star has fairly sharp lines and the plates were measured on the comparator.
- No. 184—Boss 5552—The lines are fair, 4549, 4481 and 3933 being present in addition to the hydrogen series.
- No. 185—Boss 5700—Very sharp 4481. The hydrogen lines also show a sharp core on plates with sufficient exposure. Re-measures were made by P.
- No. 186—Boss 5771—All the plates of this star are rather weak but there are many good lines present in the spectrum. The star is one of a visual double. The second star is F5-type and measures of its spectrum so far show it to be constant velocity. The separation is 4 seconds of arc.
- No. 187—Boss 5936—The K line and the hydrogen lines are of the usual strength for this type but there is scarcely any trace of 4481. Measures on the whole are accordant.

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THE ORBITS OF THE SPECTROSCOPIC COMPONENTS OF BOSS 4622

BY W. E. HARPER

This star ($1900\ \alpha = 18^h\ 13.0^m$, $\delta = +56^\circ\ 34'$, type Fo, visual magnitude 6.41), was discovered to be a spectroscopic binary from the first plate made of it by the writer in July, 1919, as the spectra of both components appeared upon the plate. Eight plates were secured that year, twenty-seven during 1920 and twenty-five during 1921, making sixty in all. Forty-eight of the plates show the lines double and twelve show them as single. Of the twelve showing single lines three were not used in the investigation as the lines were fuzzy, due as later seen from the observations occurring at phases when only partial superposition of the lines would occur.

The component spectra are quite similar and consist, in addition to the hydrogen series, of the numerous metallic lines usually occurring in F-type spectra. It cannot be said that the lines are fuzzy in character and poor for measurement but they are certainly far from being sharp and as the majority of the plates are a little underexposed for the most accurate measurement the probable errors which have been determined for the plates are large, but not surprisingly so. There is a very slight difference between the two components and the stronger, designated component I, has a probable error of a plate of ± 4.2 km. per sec., while that for component II is ± 4.6 km. per sec. Fortunately the range in velocity is large, being over 200 km. in each component, and thus the probable errors of the elements are satisfactorily small.

Considerable time was spent obtaining the period. Where the lines are nearly equal in intensity it is hard to distinguish the components and the difficulty is accentuated when you have a host of lines, each set with a wide range of displacements, crowded upon each other in the low dispersion of a single prism which was used throughout. The first period suggested was a 2-day one as it seemed that the spectra alternated on consecutive days on the plates of the first year. For some reason this suggested period was dropped, probably because the main series in 1920 suggested another. These observations

were taken in a leisurely way,—just when the writer was observing, and when plotted consecutively on cross-section paper seemed to indicate a 72-day period. This was felt to be the period without a doubt and as there were a few gaps in the curve it was decided to wait the necessary time so as to fill them up. Fortunately these, when obtained, fell so much off the curve that the period of 72 days was questioned. It was then found that as good a curve could be obtained by using a period greater than the even day by $1/72$ day. The 1921 series, however, could not be brought into complete accord and finally a period of 2.0476 days was found which satisfied perfectly the observations of all three years. No attempt has been made to improve on this value by incorporating the period in the least squares solution.

In the following table of observations all the essential data are given. The phases are reckoned from the time of periastron given in the final elements, using the period 2.0476 days. The plates were all measured on the Toepfer measuring machine and the number of lines used is given in columns 6 and 10. The weights given the plates are based partly on the number of lines used and partly on a number of other considerations and appear in columns 7 and 11 while the residuals in the sense observed minus computed were scaled from a large-scale curve representing the final elements.

The observations for each component were grouped according to phase into 14 normal phases. While the same grouping of plates was made for each component yet the different relative weights of the plates in the two cases generally resulted in different mean phases. Thus they are shown separately in the table, numbers 1–14 representing component I and numbers 15–28 component II. Since the two groups of plates which show single lines may with justice be assigned to either component they have been divided between the two components with approximately the same weight to each.

OBSERVATIONS OF BOSS 4622

Plate Number	Date	Julian Date	Phase	Component I				Component II			
				Vel.	n	Wt.	O-C	Vel.	n	Wt.	O-C
2294	1919, July 7	2,422,147.816	.186	- 83.4	10	1.0	- 4.4	+ 66.3	10	1.0	- 1.2
2370	" 14	154.814	1.041	+ 87.1	6	0.5	+ 0.1	-109.5	6	0.5	- 2.0
2388	" 15	155.832	.012	-110.1	7	0.5	+ 2.4	+108.1	4	0.5	+ 8.6
2404	" 17	157.800	1.980	-110.9	4	0.5	+ 6.9				
2419	" 18	158.788	.920	+ 96.2	8	1.0	+ 4.2	-116.2	8	1.0	- 4.0
2466	" 21	161.716	1.801	-102.9	4	0.5	- 2.4	+ 95.2	3	0.5	+ 7.8
2485	" 22	162.745	.782	+ 84.2	7	1.0	+ 0.8	-107.4	7	0.6	- 4.9
2550	" 28	168.694	.588	+ 48.0	2	0.5	+ 3.0	- 82.0	2	0.2	-18.0
4318	1920, May 19	464.909	1.949	-114.1	7	0.5	+ 3.5	+100.7	7	1.0	- 2.8
4373	" 31	476.900	1.654	- 74.7	13	1.0	-19.0	+ 54.9	11	1.0	+15.9
4405	June 11	487.888	.356	- 14.8	6	0.5					
4420	" 17	493.861	.187	- 85.0	4	0.5	- 6.0	+ 58.6	6	1.0	- 5.3
4463	" 25	501.841	2.024	-113.0	12	1.0	+ 2.0	+102.3	11	1.0	+ 0.3
4484	" 28	504.849	.937	-110.2	4	0.5	+ 2.3	+100.7	9	1.0	+ 8.4
4536	July 2	508.770	.762	-109.0	7	1.0	- 8.5	+ 86.3	12	1.0	+ 5.3
4570	" 5	511.819	1.764	- 91.6	14	1.0	+ 1.0	+ 75.5	9	1.0	- 4.3

OBSERVATIONS OF BOSS 4622—*Concluded*

Plate Number	Date	Julian Date	Phase	Component I				Component II			
				Vel.	n	Wt.	O—C	Vel.	n	Wt.	O—C
4585	1920, July 6	512.801	.698	+ 73.9	6	1.0	+ 3.4	-102.6	1	0.2	-12.6
4599	" 7	513.868	1.766	- 93.2	13	1.5	- 0.2	+ 77.9	12	1.0	- 0.5
4622	" 14	520.793	.500	- 5.5	7						
4634	" 16	522.764	.423	- 7.3	9	1.0					
4664	" 22	528.812	.328	- 19.5	8						
4752	Aug. 1	538.778	.056	-104.6	11	1.0	+ 2.0	+108.3	7	1.0	+15.3
4763	" 2	539.773	1.051					-113.0	4	0.5	- 6.5
4770	" 3	540.797	.028	-110.5	18	1.7	0.0	+ 97.6	13	1.2	- 0.5
4781	" 4	541.799	1.030	+ 89.4	14	1.0	+ 1.5	-103.7	9	1.0	+ 4.8
4879	" 13	550.677	1.718	- 94.3	11	1.0	-11.8	+ 57.9	7	1.0	-11.0
4987	Sept. 1	569.680	.244	- 71.8	6	1.0	- 9.4	+ 60.4	2	0.5	+11.8
5036	" 5	573.669	.138	- 93.8	5	0.5	- 2.8				
5046	" 6	574.672	1.141	+ 76.9	16	1.5	+ 2.8	-103.4	14	1.5	- 9.4
5080	" 24	592.710	.751	+ 80.9	13	1.5	+ 1.7	- 95.8	8	0.7	+ 2.7
5109	" 28	596.659	.605	+ 44.2	5	0.5	- 6.0	- 56.5	5	0.5	+11.0
5145	Oct. 8	606.653	.361	- 12.8	13	1.2					
5191	" 12	610.650	.262	- 68.6	8	1.0	-11.0	+ 48.3	5	0.5	+ 5.0
5406	Nov. 5	634.620	1.709	- 87.4	10	1.0	- 7.2	+ 73.3	8	1.0	+ 6.4
5449	" 9	638.645	1.639	- 63.9	10	1.0	- 0.9	+ 38.6	5	0.5	- 7.6
5780	1921, Mar. 19	767.050	.045	- 99.0	4	0.3	+ 8.0	+ 80.0	3	0.3	-16.2
5890	April 7	787.959	1.478	- 0.5	15	1.5					
5893	" 8	788.029	1.548	- 10.2	16						
5924	" 15	795.907	1.235	+ 68.6	7	0.7	+13.0	- 75.7	7	0.7	- 1.3
5927	" 16	796.001	1.329	+ 34.8	1	0.3	+ 2.3	- 40.2	1	0.3	+10.0
5973	May 2	812.797	1.745	- 82.2	10	1.0	+ 6.0	+ 75.1	6	1.0	- 0.7
5976	" 2	812.971	1.919	-108.5	15	1.5	+ 7.5	+103.9	9	1.0	+ 0.9
6018	" 11	821.815	.525	+ 16.2	2	0.5	-10.8	- 51.5	2	0.3	- 6.0
6044	" 17	827.781	.348	- 13.8	14	1.5					
6052	" 20	830.797	1.316	+ 42.8	3	0.4	+ 6.8	- 49.4	3	0.4	+ 4.6
6058	" 20	830.964	1.484	- 14.9	16	1.5					
6069	" 23	833.768	.192	- 76.7	16	1.5	+ 0.7	+ 66.1	10	1.0	+ 3.1
6076	" 23	833.957	.381	- 10.7	11	1.0					
6127	June 1	842.765	.999	+ 99.6	9	1.0	+ 9.0	-118.9	6	1.0	- 8.2
6138	" 7	848.777	.868	+ 97.8	12	1.0	+ 6.9	-119.0	9	1.0	- 8.3
6182	July 3	874.948	.420	- 2.6	13	1.3					
6185	" 6	877.808	1.232	+ 56.4	4	0.6	+ 0.2	- 72.0	4	0.6	+ 3.0
6187	" 8	879.718	1.095	+ 89.2	5	0.5	+ 8.0	- 97.6	5	0.5	+ 3.4
6217	" 11	882.757	.039	-105.4	13	1.5	+ 4.0	+ 94.3	9	1.0	- 1.7
6331	" 28	899.877	.778	+ 84.1	7	1.0	+ 1.1	-102.1	6	0.5	0.0
6515	Sept. 6	939.779	1.776	- 94.8	2	0.5	+ 1.0	+ 77.4	5	0.5	- 4.8
6552	" 12	945.751	1.605	- 57.2	8	1.0	- 4.1	+ 36.3	3	0.5	- 1.0
6577	" 16	949.715	1.474	- 11.2	23	2.0					
6615	" 30	963.624	1.049	+ 85.7	9	1.0	- 0.3	-106.4	6	0.5	0.0
6668	Oct. 3	2,422,966.761	.091	-102.9	7	0.5	- 2.4	+ 87.2	7	1.0	+ 0.8

NORMAL PLACES

	Mean Phase	Mean Velocity	Wt.	O—C	
				Prel.	Final
1.....	1.478	— 9.10	2.5	+4.40	+ 4.28
2.....	1.633	— 65.27	3.0	—4.77	— 3.84
3.....	1.734	— 88.89	4.0	—2.99	— 0.65
4.....	1.825	—102.08	5.0	+0.32	+ 4.01
5.....	1.992	—112.24	2.5	—0.04	+ 4.99
6.....	.035	—107.91	3.5	—2.61	+ 2.13
7.....	.113	— 95.58	4.0	—2.48	+ 1.23
8.....	.227	— 72.97	3.5	—6.77	— 4.89
9.....	.382	— 9.98	3.5	+9.13	+ 8.69
10.....	.572	+ 36.13	1.5	—3.47	— 4.21
11.....	.752	+ 80.78	4.5	+0.68	+ 1.80
12.....	.954	+ 95.75	4.0	+0.95	+ 3.35
13.....	1.093	+ 82.63	3.5	—1.27	+ 0.94
14.....	1.264	+ 54.65	2.0	+5.05	+ 5.84
15.....	1.478	— 9.10	2.5	—9.30	— 5.60
16.....	1.638	+ 46.15	2.0	—4.85	— 1.31
17.....	1.734	+ 70.45	4.0	—5.65	— 3.06
18.....	1.821	+ 88.60	4.0	—4.10	— 2.65
19.....	1.986	+101.23	3.0	—2.57	— 2.26
20.....	.036	+101.13	3.0	+4.73	+ 5.28
21.....	.126	+ 76.60	4.0	—4.30	— 2.85
22.....	.222	+ 60.20	2.0	+3.40	+ 5.91
23.....	.382	— 9.98	3.0	—16.08	—11.92
24.....	.578	— 60.10	1.0	—3.00	+ 0.24
25.....	.762	—101.50	2.0	—2.10	— 1.34
26.....	.954	—114.45	4.0	—1.25	— 2.12
27.....	1.094	—105.24	3.5	—3.44	— 4.01
28.....	1.264	— 64.05	2.0	+1.85	+ 3.43

PRELIMINARY ELEMENTS

Period	$P = 2.0476$ days
Eccentricity	$e = .02$
Longitude of periastron	$\omega_1 = 195^\circ$
“ “	$\omega_2 = 15^\circ$
Velocity of system	$\gamma = -6.80$ km.
Semi-amplitude of range	$K_1 = 103.8$ km.
“ “	$K_2 = 108.7$ km.
Periastron passage	$T = \text{J.D. } 2,422,147.630$

Making the following transformations for homogeneity the 28 observation equations were built up according to the formula for double spectra* with the weights of each as given in the table of normal places. Owing to the small value of the eccentricity, periastron was considered fixed.

$$\begin{aligned}x &= \delta\gamma \\y &= \delta K_1 \\z &= \delta K_2 \\u &= 100\delta e \\v &= 100\delta\omega\end{aligned}$$

OBSERVATION EQUATIONS FOR BOSS 4622

1	1.000x	— .064y	.000z	+ .980u	— 1.032v	— 4.4 = 0
2	1.000	— .517	.000	+ .783	— .895	+ 4.8
3	1.000	— .762	.000	+ .226	— .689	+ 3.0
4	1.000	— .921	.000	— .375	— .443	— 0.3
5	1.000	— 1.015	.000	— 1.037	+ .092	0.0
6	1.000	— .949	.000	— .908	+ .385	+ 2.6
7	1.000	— .831	.000	— .535	+ .610	+ 2.5
8	1.000	— .572	.000	+ .227	+ .870	+ 6.8
9	1.000	— .118	.000	+ .999	+ 1.038	— 9.1
10	1.000	+ .447	.000	+ .749	+ .924	+ 3.5
11	1.000	+ .837	.000	— .283	+ .541	— 0.7
12	1.000	+ .979	.000	— 1.217	— .053	— 1.0
13	1.000	+ .874	.000	— .832	— .461	+ 1.3
14	1.000	+ .544	.000	+ .031	— .852	— 5.0
15	1.000	.000	+ .064	— 1.026	+ 1.080	+ 9.3
16	1.000	.000	+ .575	— .797	+ .928	+ 4.8
17	1.000	.000	+ .762	— .237	+ .722	+ 5.7
18	1.000	.000	+ .915	+ .366	+ .476	+ 4.1
19	1.000	.000	+ 1.017	+ 1.080	— .077	+ 2.6
20	1.000	.000	+ .949	+ .949	— .405	— 4.7
21	1.000	.000	+ .806	+ .475	— .676	+ 4.3
22	1.000	.000	+ .585	— .202	— .901	— 3.4
23	1.000	.000	+ .118	— 1.046	— 1.087	+ 16.1
24	1.000	.000	— .463	— .757	— .958	+ 3.0
25	1.000	.000	— .852	+ .357	— .539	+ 2.1
26	1.000	.000	— .979	+ 1.274	+ .055	+ 1.2
27	1.000	.000	— .874	+ .870	+ .485	+ 3.4
28	1.000	.000	— .544	— .033	+ .880	— 1.9

*Dominion Observatory Publications, Vol. I, p. 327.

From these were obtained the normal equations

$$\begin{array}{rcccccccl}
 8.700x & - & .844y & + & .843z & + & .116u & + & .255v & + & 16.215 & = & 0 \\
 & & 2.760 & & + .000 & & + .161 & & + .011 & & - 4.701 & & \\
 & & & & 2.422 & & - .143 & & - .109 & & + 3.145 & & \\
 & & & & & & 5.017 & & - .212 & & - 9.179 & & \\
 & & & & & & & & 4.016 & & + .089 & &
 \end{array}$$

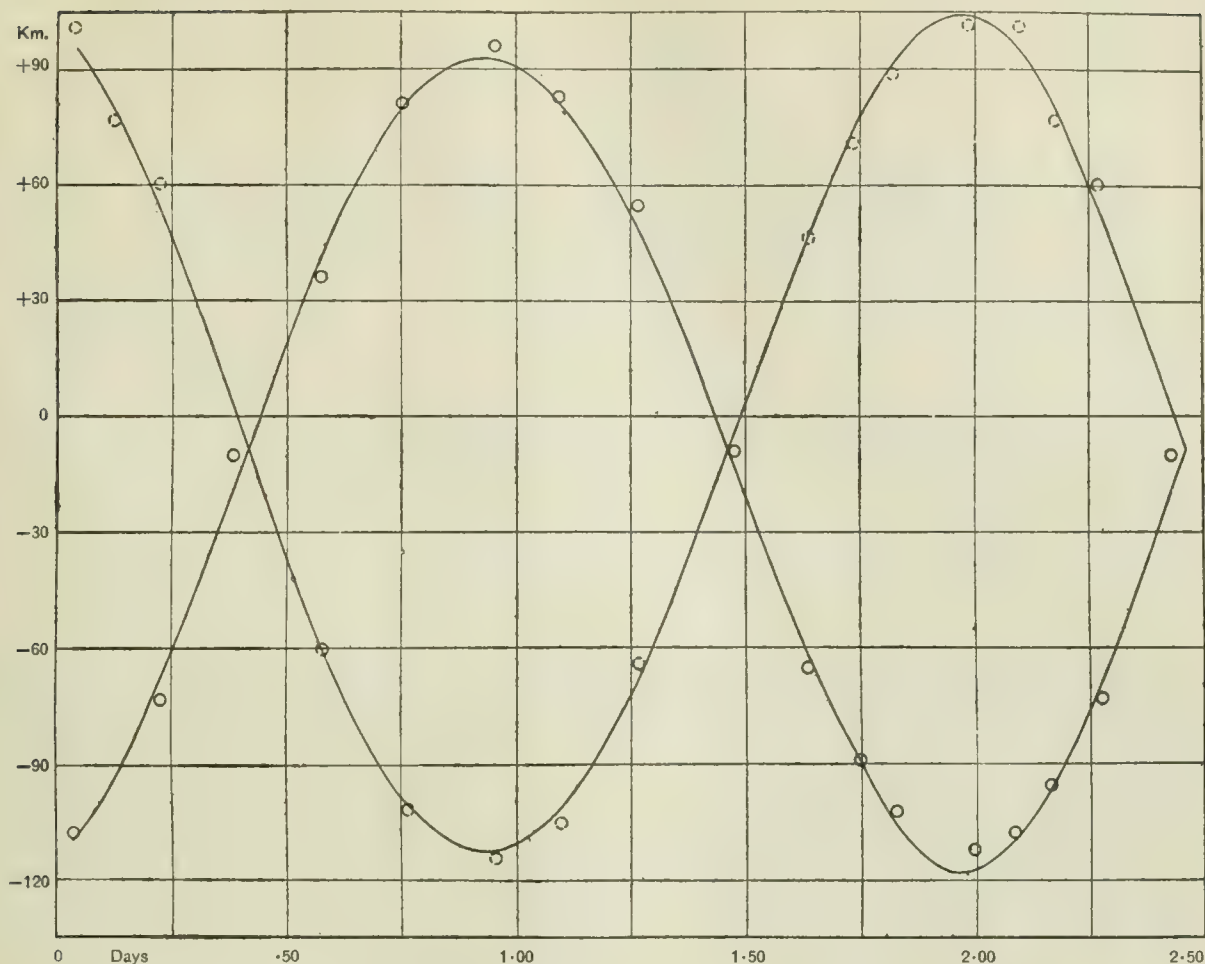
resulting in corrections as follows

$$\begin{aligned}
 \delta\gamma &= - 1.71 \text{ km.} \\
 \delta K_1 &= + 1.29 \text{ km.} \\
 \delta K_2 &= - 0.58 \text{ km.} \\
 \delta e &= + .019 \\
 \delta\omega &= + 0^\circ.10
 \end{aligned}$$

The final values, then, with their probable errors, are the following:

FINAL ELEMENTS

$$\begin{aligned}
 P &= 2.0476 \text{ days} \\
 e &= .039 \pm .008 \\
 \omega_1 &= 195^\circ.10 \pm 0^\circ.52 \\
 \omega_2 &= 15^\circ.10 \pm 0^\circ.52 \\
 \gamma &= -8.51 \text{ km.} \pm 0.63 \text{ km.} \\
 K_1 &= 105.09 \text{ km.} \pm 1.10 \text{ km.} \\
 K_2 &= 108.12 \text{ km.} \pm 1.18 \text{ km.} \\
 T &= \text{J.D. } 2,422,147.630 \\
 a_1 \sin i &= 2,956,600 \text{ km.} \\
 a_2 \sin i &= 3,041,900 \text{ km.} \\
 m_1 \sin^3 i &= 1.043 \odot \\
 m_2 \sin^3 i &= 1.013 \odot
 \end{aligned}$$



Velocity Curves of Boss 4622, With Grouped Observations.

The solution improved the agreement considerably, the sum of the squares of the residuals for the normal places being reduced from 2226.6 to 1636.5, or about 26 per cent. The accompanying curve represents the final elements, the observations as grouped being shown.

Though our empirical curves connecting line intensities with absolute magnitudes are as yet far from complete, yet an inspection of the lines would suggest a preliminary value in the neighbourhood of $+1.5$ for the combined absolute magnitude, in which case the parallax would be $0''.016$. This of course must not be considered as definite.

Dominion Astrophysical Observatory,
Victoria, B.C.
Nov. 12, 1921.



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ORBIT OF THE SPECTROSCOPIC BINARY H.R. 5992

BY J. W. CAMPBELL

The star H.R. 5992 ($1900\ \alpha = 16^h\ 0^m\cdot 8$, $\delta = + 8^\circ\ 22'$, visual magnitude 6.1, type A) was on a list of eight stars whose radial velocities the writer undertook to determine during his three months' association with the Dominion Astrophysical Observatory at Victoria in the summer of 1921. It was found to be a spectroscopic binary from the first two plates secured in June. Owing to cloudy weather not many plates were secured in that month, but the kind co-operation of the members of the permanent staff of the observatory made it possible to secure a good run of plates during the favorable weather of July and August, and to get a good distribution along the velocity curve after a period of approximately 8.8 days had become evident.

In all, twenty plates were secured, and the orbit determined from these. Owing to the brevity of the interval in which the observations were made the period was included in the least squares solution. In the first solution there was unsatisfactory agreement between the residuals from the ephemeris and those from the observation equations and a second solution was made in which the agreement was satisfactory.

The following is the table of observations in which the phases are those given by the corrected period and periastron passage.

OBSERVATIONS OF H.R. 5992

Plate Number	Date	Julian Date	Phase	Lines	Wt.	Velocity	O—C
6147	1921, June 11	2,422,852.745	6.041	8	$\frac{1}{2}$	-35.1	+3.1
6160	" 18	859.777	4.218	6	$\frac{1}{2}$	-19.7	-2.0
6161	" 22	863.715	8.156	16	1	-49.6	+1.7
6175	July 1	872.751	8.337	5	$\frac{1}{2}$	-47.1	+0.2
6176	" 2	873.804	0.535	21	1	+ 0.5	+1.1

OBSERVATIONS OF H.R. 5992—*Concluded*

Plate Number	Date	Julian Date	Phase	Lines	Wt.	Velocity	O C
6183	1921, July 5	876.827	3.558	10	1	-12.0	-1.5
6184	" 6	877.771	4.502	8	$\frac{1}{2}$	-20.5	+0.3
6188	" 8	879.750	6.481	20	1	-45.3	-2.0
6194	" 9	880.743	7.474	21	1	-53.4	-0.3
6201	" 10	881.709	8.440	14	1	-44.2	-0.1
6215	" 11	882.709	0.585	15	1	+ 0.7	-0.2
6224	" 12	883.718	1.594	15	1	+ 9.0	+0.8
6232	" 13	884.722	2.598	12	1	- 1.2	-0.8
6240	" 14	885.736	3.612	11	1	- 8.8	+2.3
6244	" 15	886.729	4.605	14	1	-19.2	+2.7
6249	" 16	887.743	5.619	12	1	-35.0	-2.0
6278	" 21	892.718	1.739	15	1	+ 5.8	-1.5
6288	" 22	893.746	2.767	12	1	- 2.0	+0.4
6328	" 28	899.792	8.813	12	1	-31.7	-4.5
6380	Aug. 6	908.724	0.035	16	1	-19.7	+3.4

The following preliminary elements were used as the basis of the second least squares solution:

$$\begin{aligned}
 P &= 8.860 \text{ days} \\
 e &= 0.38 \\
 \omega &= 265^\circ \\
 T &= \text{J.D. } 2,422,846.740 \\
 K &= 31.5 \text{ km.} \\
 \gamma &= -21.5 \text{ km. per sec.}
 \end{aligned}$$

OBSERVATION EQUATIONS

1	1.000x	-0.178y	-0.248z	+1.368u	+1.166v	-1.882w	-7.400	= 0
2	1.000	-0.606	+1.349	+1.148	+0.336	-1.241	-2.900	
3	1.000	+0.654	+1.343	+1.106	+0.410	-1.139	-1.600	
4	1.000	+0.946	-0.520	+0.174	-0.060	+0.162	-0.700	
5	1.000	+0.922	-0.684	+0.082	-0.100	+0.218	+1.800	
6	1.000	+0.685	-0.999	-0.317	-0.213	+0.561	+1.300	
7	1.000	+0.633	-0.972	-0.367	-0.170	+0.361	+0.500	
8	1.000	+0.367	-0.647	-0.537	-0.113	+0.375	+2.100	
9	1.000	+0.351	-0.620	-0.544	-0.147	+0.376	-1.600	
10	1.000	+0.141	-0.249	-0.606	-0.050	+0.381	+2.700	
11	1.000	+0.047	-0.073	-0.618	-0.119	+0.383	+0.500	
12	1.000	+0.013	-0.009	-0.620	-0.154	+0.384	-1.900	
13	1.000	-0.344	+0.632	-0.571	-0.165	+0.402	+2.700	
14	1.000	-0.505	+0.863	-0.503	-0.025	+0.415	-2.300	
15	1.000	-0.660	+1.001	-0.400	-0.136	+0.411	+3.000	

OBSERVATION EQUATIONS—*Concluded.*

16	1.000	-0.987	+0.572	+0.078	-0.086	+0.254	+0.800
17	1.000	-0.970	-0.887	+0.730	+0.081	-0.475	-2.400
18	1.000	-0.866	-1.217	+0.932	+0.220	-0.846	-1.600
19	1.000	-0.782	-1.301	+1.042	+0.377	-1.079	-1.900
20	1.000	-0.298	-0.568	+1.343	+0.966	-1.821	+0.900

where

$$\begin{aligned} x &= \delta\gamma \\ y &= \delta K \\ z &= K\delta e \\ u &= K\delta\omega \\ v &= \frac{100 K}{(1-e^2)^{\frac{3}{2}}} \delta\mu \\ w &= \frac{K \mu}{(1-e^2)^{\frac{3}{2}}} \delta T \end{aligned}$$

Equations 10, 11, 14, 18 are those of weight $\frac{1}{2}$.

NORMAL EQUATIONS

18.000x	+0.366y	-2.896z	+3.318u	+2.005v	- 3.967w	- 7.650	=0
	7.383	-0.245	-1.304	-0.760	+ 1.565	+ 2.227	
		11.848	-0.256	-0.167	- 0.057	+ 1.656	
			10.503	+4.833	-11.190	-21.216	
				2.953	- 5.925	-11.676	
					13.019	+24.875	

The solution of the normal equations gave the corrections

$$\begin{aligned} \delta\gamma &= -0.04 \text{ km.} \\ \delta K &= +0.12 \text{ km.} \\ \delta e &= -0.004 \\ \delta\omega &= +0^\circ.41 \\ \delta P &= -0.005 \text{ days} \\ \delta T &= -0.036 \text{ days} \end{aligned}$$

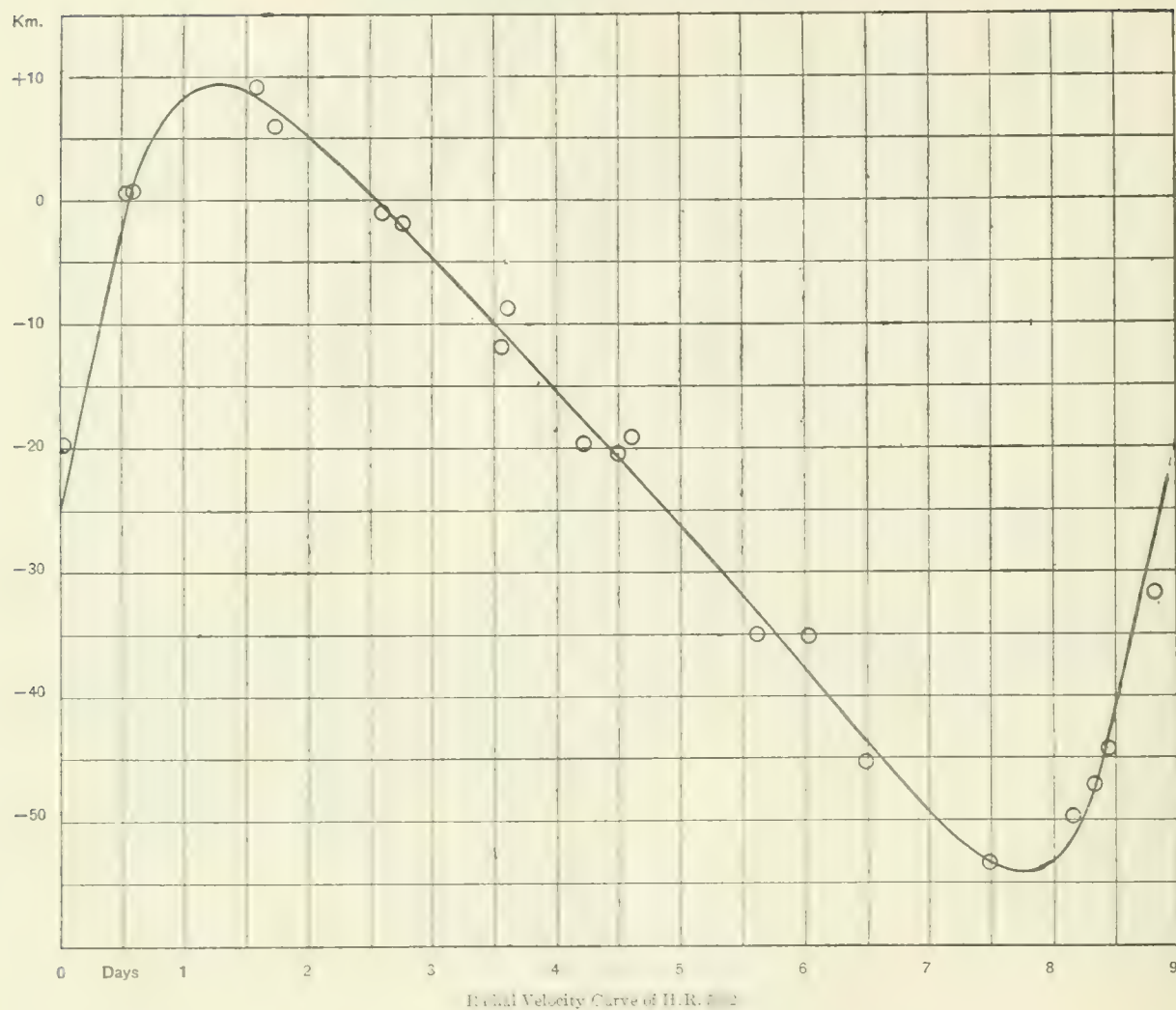
and the final values of the elements, with their probable errors, are

$$\begin{aligned} P &= 8.855 & \pm 0.0113 \text{ days} \\ e &= 0.376 & \pm 0.014 \\ \omega &= 265^\circ.41 & \pm 3^\circ.49 \\ T &= \text{J.D. } 2,422,846.704 & \pm 0.104 \text{ days} \\ K &= 31.62 & \pm 0.56 \text{ km.} \\ \gamma &= -21.54 & \pm 0.36 \text{ km. per sec.} \end{aligned}$$

$$a \sin i = 3,568,000 \text{ km.,}$$

$$\frac{m_1^3 \sin^3 i}{(m+m_1)^2} = .023 \odot$$

The solution reduced Σpv^2 from 118.4 to 69.7, and the probable error of a plate is ± 1.36 km. per sec.



It is with pleasure that I express my appreciation of the kindness and courtesy shown me (while at the observatory), by Dr. Plaskett and all the members of his staff. They greatly helped to make my time both profitable and congenial.

Dominion Astrophysical Observatory,
Victoria, B.C.
Nov. 1921.

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ORBIT OF THE SPECTROSCOPIC BINARY BOSS 5442

BY REYNOLD K. YOUNG

Boss 5442, R.A. (1900) $21^{\text{h}} 04^{\text{m}} \cdot 4$, Dec. $+29^{\circ} 48'$, mag. $5 \cdot 6$, type Ao, was discovered to be a spectroscopic binary from plates taken in 1918. The spectrum given as type Ao is better classified as B8. There are present the K line of calcium which is sharp and narrow, the hydrogen series of which both $H\delta$ and $H\gamma$ are good, a fine 4481 and 4472 and the two silicon lines 4128 and 4131. The iron line 4549 and some others are present on a few plates but are very weak and of little use for radial velocity determinations.

Observation of the star was begun in July, 1920, with a view to obtaining the orbit and between that date and August, 1921, forty-nine spectrograms were secured. These observations and the velocities obtained from them are listed below in the table of observations.

OBSERVATIONS OF BOSS 5442

Plate Number	Date	Julian Date G.M.T.	Velocity	No. of Lines	Wt.	Phase from 2520.0	Residual O—C
188	1918, June 18	2,421,763.956	$-10 \cdot 8$	6	1	2.793	$+10 \cdot 7$
298	July 2	1,777.940	$-47 \cdot 5$	4	1	0.209	$+ 2 \cdot 8$
328	" 11	1,786.907	$-32 \cdot 8$	6	1	2.548	$-21 \cdot 8$
535	Aug. 30	1,836.793	$-14 \cdot 1$	7	1	2.729	$+ 4 \cdot 0$
2355	1919, July 13	2,153.901	$-11 \cdot 1$	5	1	1.722	$- 4 \cdot 1$
4627	1920, July 14	2,520.888	$-46 \cdot 1$	6	1	0.888	$- 2 \cdot 6$
4647	" 18	2,524.864	$-38 \cdot 2$	6	1	1.550	$-25 \cdot 2$
4658	" 21	2,527.871	$-37 \cdot 1$	2	$\frac{1}{2}$	1.244	$- 9 \cdot 4$
4674	" 23	2,529.845	$-45 \cdot 7$	6	1	3.218	$- 4 \cdot 7$
4699	" 25	2,531.859	$-21 \cdot 9$	8	1	1.918	$-19 \cdot 3$
4719	" 26	2,532.976	$-34 \cdot 9$	6	1	3.035	$- 2 \cdot 3$
4727	" 27	2,533.884	$-55 \cdot 3$	6	1	0.629	$- 4 \cdot 4$

OBSERVATIONS OF BOSS 5442—*Concluded*

Plate Number	Date	Julian Date G.M.T.	Velocity	No. of Lines	Wt.	Phase from 2520.0	Residual O—C
4733	1920, July 28	2,534.746	-20.2	6	1	1.491	- 4.2
4738	" 28	2,534.898	-19.1	6	1	1.643	- 9.3
4759	Aug. 1	2,538.934	-18.6	8	1	2.366	-13.8
4808	" 7	2,541.899	-21.0	5	1	1.703	-16.3
4820	" 8	2,545.849	-26.1	8	1	2.653	-11.1
4832	" 9	2,546.873	-58.3	5	1	0.363	- 5.8
4857	" 11	2,548.676	- 3.9*	3	$\frac{1}{2}$	2.166	- 2.2
4683	" 11	2,548.877	-12.5	5	1	2.367	- 7.5
4873	" 12	2,549.869	-46.0	6	1	0.046	0.0
4884	" 13	2,550.901	-37.9	6	1	1.078	- 2.3
4891	" 15	2,552.787	-38.0	5	1	2.964	- 8.5
4896	" 18	2,555.776	-23.3	5	1	2.639	- 8.8
4913	" 20	2,557.841	-24.5	5	1	1.390	- 4.2
4978	" 31	2,568.763	- 4.8	6	1	2.371	- 0.0
5027	Sept. 3	2,571.752	- 6.7	7	1	2.047	- 5.3
5039	" 5	2,573.779	-50.3	5	1	0.760	- 3.0
5055	" 6	2,574.853	-10.6	5	1	1.834	- 6.6
5113	" 28	2,596.776	-35.3	5	1	0.561	+16.5
5194	Oct. 12	2,610.762	-18.4	6	1	1.292	+ 6.6
5251	" 24	2,622.658	-24.2*	1	$\frac{1}{2}$	3.247	+18.0
6267	1921, July 20	2,891.719	-51.3	6	1	0.585	+ 1.0
6268	" 20	2,891.749	-47.8	6	1	0.615	+ 3.2
6269	" 20	2,891.778	-45.7	5	1	0.644	+ 4.7
6270	" 20	2,891.802	-48.1	5	1	0.668	+ 1.7
6272	" 20	2,891.876	-46.8	6	1	0.742	+ 1.2
6273	" 20	2,891.899	-37.7	6	1	0.765	+ 9.4
6274	" 20	2,891.922	-45.3	5	1	0.788	+ 1.6
6275	" 20	2,891.945	-43.1	6	1	0.811	+ 3.0
6276	" 20	2,891.968	-31.3}	6}	1}	0.834	+14.4
			-30.2}	6}	1}		
6287	" 22	2,893.718	- 6.3	5	1	2.584	+ 5.7
6319	" 27	2,898.714	-34.8	6	1	0.952	+ 6.2
6320	" 27	2,898.734	-20.2	5	1	0.972	+19.8
6325	" 28	2,899.711	+ 3.0	6	1	1.949	+ 5.0
6335	" 28	2,899.972	+ 6.4	6	1	2.210	+ 9.0
6337	" 29	2,900.705	-18.7	6	1	2.941	+ 9.3
6343	" 29	2,900.989	-28.2	6	1	3.228	+12.8
6344	" 30	2,901.739	-34.9	6	1	0.664	+15.1
6349	" 30	2,901.982	-28.5	5	1	0.907	+14.0
6354	" 31	2,902.822	+ 9.2	5	1	1.747	+15.2
6361	" 31	2,902.990	+ 3.7	5	1	1.915	+ 6.2
6366	Aug. 1	2,903.951	-14.3	5	1	2.876	+11.0
6370	" 2	2,422,904.859	-37.0	4	$\frac{1}{2}$	0.470	+15.7

It proved a difficult task to find the period of the star. It is not certain that the observations can be represented by simple elliptic motion. There can be no doubt of the existence of the period 3.3137 days and on this basis the observations have been grouped into eleven normal places as given below and orbital elements determined from them. The curve given at the end of the paper shows how the period chosen harmonizes the velocities. The early observations are shown by a large filled circle, the 1919 observations by a small circle and those of 1920 by an open circle. The graph of the normal places is also given.

NORMAL PLACES

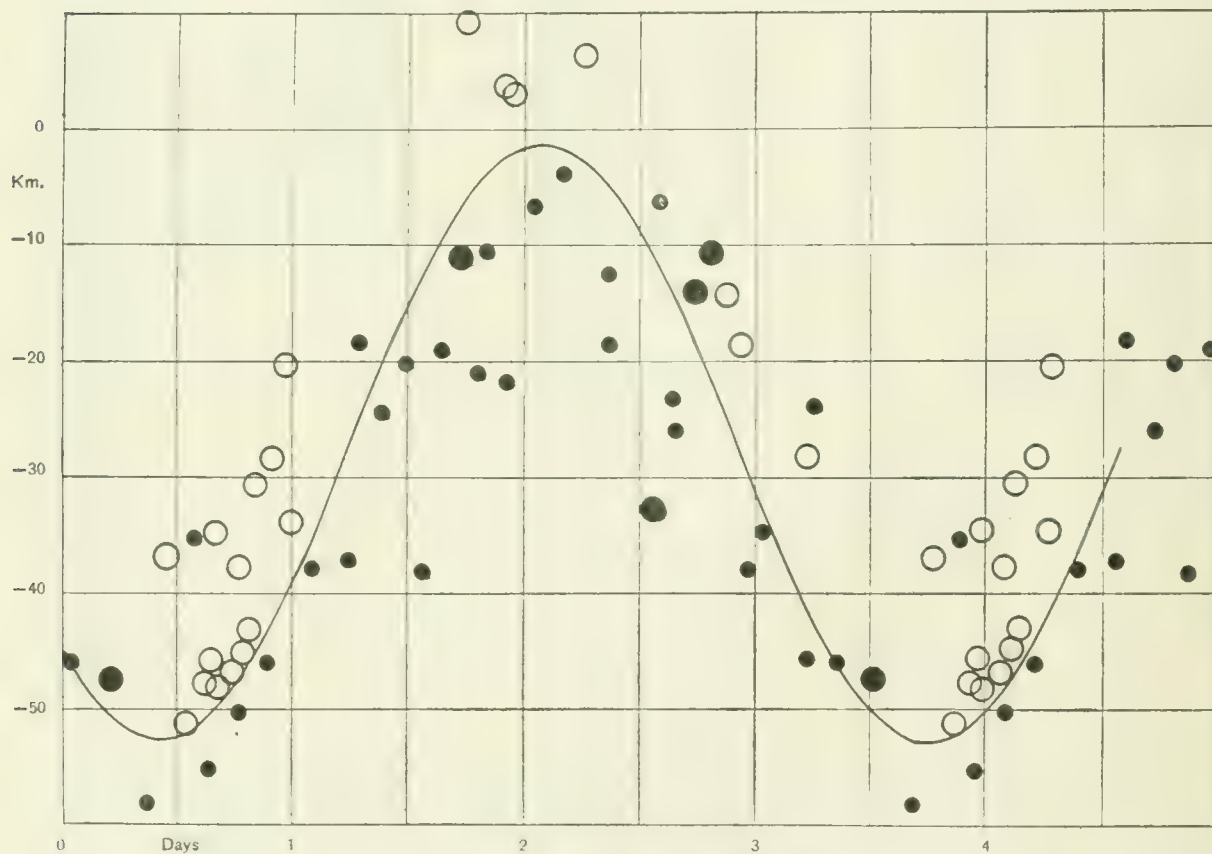
	Phase from J.D. 2,422,520.0	Velocity km.	No. of Plates	Residual O—C
1.....	0.286	-52.9	2	- 0.8
2.....	0.604	-44.4	8	+ 6.6
3.....	0.842	-38.4	10	+ 6.6
4.....	1.251	-29.5	3	- 3.5
5.....	1.561	-25.8	3	-14.0
6.....	1.785	-11.1	5	- 6.6
7.....	2.019	- 1.0	4	+ 0.1
8.....	2.329	- 7.4	4	- 2.8
9.....	2.657	-19.9	6	- 3.8
10.....	2.952	-26.5	4	+ 3.1
11.....	3.263	-37.7	4	+ 5.4

The approximate elements which satisfy these places are

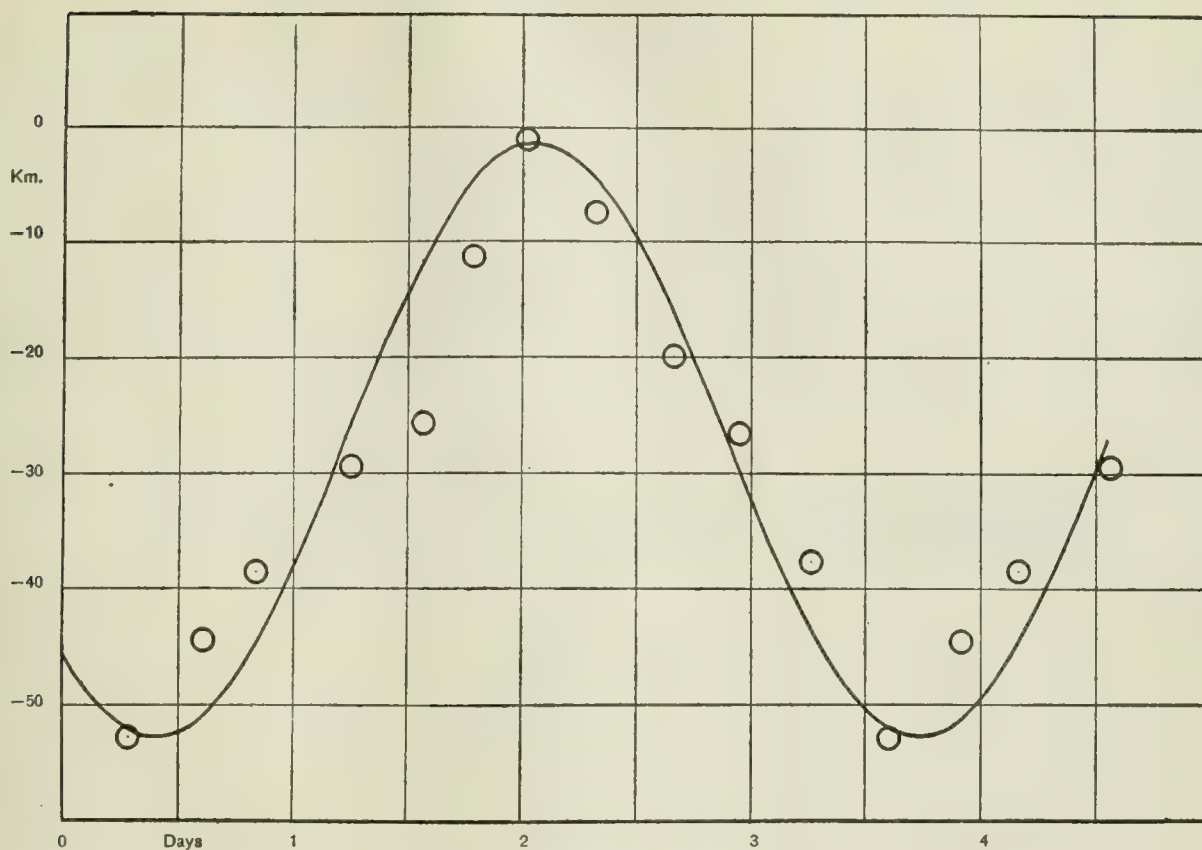
Period	$P = 3.3137$ days
Eccentricity	$e = 0.0$
Perihelion	$T = \text{J.D. } 2,422,521.230$
Semi-amplitude	$K = 26$ km.
Velocity of system	$\gamma = -26.8$ km.
$a \sin i$	$= 1,185,000$ km.
$\frac{m_1^3 \sin^3 i}{(m + m_1)^2}$	$= .0060 \odot$

It has not seemed necessary to perform the labour of a least-squares solution in order to render the agreement between the normal places and the representation by the elements the best possible because the elements are obviously approximate. The disposition of the normal places suggests the blending effect of a secondary component, unresolved but affecting the measures. It is well known that the general tendency of an unresolved component is to sharpen the curve at minimum and maximum. The plates have been re-examined to detect the presence of the secondary but no certain trace of it was found. In estimating the value of K , however, the curve was drawn through the maximum and minimum velocities tacitly assuming that the measures were affected by an unseen secondary.

Certain features of the plot of the individual observations are worthy of note. While all the observations conform in a general way to the adopted period, yet the range of the discordance is very large, much larger than to be expected from the character of the lines. The 1920 observations, most of which were taken on two nights, are distinctly above the mean for the 1919 observations, and moreover they indicate a slightly larger range. These features recall the behaviour of the binary 12 Lacertae. The latter binary was shown to have a variable amplitude and that succeeding revolutions of the star did not always produce the same shaped curve. If such is the case with Boss 5442 it would be an exceedingly difficult task to establish the fact with certainty, for the period being over three days it is impossible to obtain a run of plates to adequately define the curve in one revolution. We have searched for a secondary period but have not found any except the long period which might account for the difference between the 1919 and 1920 observations.



Radial Velocity Curve of Boss 5442
Showing the Individual Observations



Radial Velocity Curve of Boss 5442
Showing the Normal Places

Dominion Astrophysical Observatory,
Victoria, B.C.
November, 1921.

DEPARTMENT OF THE INTERIOR
CANADA

HON. CHARLES STEWART, Minister;

W. W. CORY, C.M.G., Deputy Minister.

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Victoria, B.C.

J. S. PLASKETT, Director.

Vol. I, No. 30

THE SPECTRA OF THREE O-TYPE STARS

BY

H. H. PLASKETT

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OTTAWA
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1922

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[Note added in proof, October 16th, 1922]—At the Yerkes meeting (September 5th-8th, 1922) of the American Astronomical Society, at which this paper was presented in abstract, Prof. H. N. Russell gave a paper on "Ionization and Pressure in the Stars." Among other things he independently considered the question of relative abundance of elements in a somewhat similar manner to its treatment in the Appendix. Prof. Russell has since read over this MS and has made a number of important suggestions and criticisms of matters treated in the Appendix and Section 7, the value and help of which the writer would like to acknowledge.

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THE SPECTRA OF THREE O-TYPE STARS

BY H. H. PLASKETT

ABSTRACT

O-Type Stars. These stars show enhanced line spectra which can be terrestrially reproduced only under extreme conditions of excitation. Their spectra afford an opportunity on the one hand to test theories on the origin of spectra, and on the other hand to ascertain some of the physical conditions in the stellar atmospheres. Three typical absorption line O-type stars were selected for detailed investigation, viz.:—10 Lacertae (Oe5), 9 Sagittae (Oe5), B.D. 35° 3930 N (Oe). Spectra were secured with one, two and three-prism dispersion. The plates were measured and the wave lengths determined in I. A. Precautions were taken to eliminate systematic errors in the wave lengths.

Pickering Components to the Balmer Lines. If the Pickering lines are due to enhanced helium, Bohr's theory predicts the existence of *enhanced helium components* about 2A to the violet of the hydrogen lines. The evidence is given in detail for the existence of these components. In 10 Lacertae components with the predicted separations and the correct intensities were found for the lines H α , H β , H γ , H δ . In 9 Sagittae a component was found for H γ , and suspected for H β , H δ . In B.D. 35° 3930N components were measured for H γ and H δ and suspected for H β . In view of the fact that the components were found to four of the Balmer lines of 10 Lacertae, and to H γ in the three stars, though they differ markedly in type, the evidence is satisfactory that Bohr's predicted components are present in stellar spectra. Their demonstrated existence makes it highly probable that the Pickering lines and 4686 are due to enhanced helium.

Rydberg Constant for Helium. The mean wave lengths (I.A.), for the enhanced helium lines in 10 Lacertae and 9 Sagittae are used to determine the value of the Rydberg constant, N₂, for helium. The position of the circle component of each line is computed on the assumptions of $\Delta\nu_H = 0.36$ and certain simple intensity relations of Sommerfeld. From the resulting wave numbers of these circle components, using Sommerfeld's theory which takes account of the relativistic variation in mass of the electron, the value of N₂, the Rydberg constant, is computed for each line. The weighted mean value is,—N₂ = 109722.3 \pm 0.44.

Spectroscopic Universal Constants. On Bohr's theory the Rydberg constant can be computed from the mass of the electron m_e, its charge e, and the value of Planck's constant h. Reversing the process, the values of these universal and other related constants can be computed with a high degree of accuracy from the spectroscopic value of Rydberg's constant. Revised values of the atomic weights of hydrogen and helium are used, and a method due to L. Flamm is followed in carrying out these computations. Birge's recomputed value of N₁ for hydrogen is used. The resulting stellar values are: N ∞ = 109737.3; the ratio of mass H atom / electron, M₁ / m_e = 1840 \pm 20; e/m_e = (1.762 \pm 0.019) $\times 10^7$ e.m.u. Assuming Millikan's value of the electronic charge, e = (4.774 \pm 0.005) $\times 10^{-10}$ e.s.u., the additional results are obtained, m_e = (9.04 \pm 0.10) $\times 10^{-28}$ gms; the radius of the electron a = (1.869 \pm 0.021) $\times 10^{-13}$ cms; h = (6.567 \pm 0.042) $\times 10^{-27}$ ergs secs; and Wien's constant in the radiation law C₂ = 1.4353 \pm 0.0093 cms degrees. These values are compared with recomputed values from Paschen's value of N₂, and also with results from other methods of determination.

Wave Lengths in O-Type Stars. All the lines that could be detected on the various plates were measured. The mean wave lengths in I.A. are given for the lines in each of the three stars, together with the probable errors of the wave lengths, the intensities of the lines, and the identifications where possible.

Physical Interpretation of Stellar Spectra. After a brief review of theories on the origin of spectra for atoms with more than one electron, Saha's ionization theory of stellar spectra is discussed. Emphasis is placed on the fact that, when an arc or a spark spectrum is on the point of disappearing, a certain minimum number of atoms

must be in a condition to absorb the arc or spark lines. The attainment of this minimum number is determined not only by the fraction of atoms once or twice ionized, but also by the density of radiation from the photosphere and the relative abundance of the element in question. The behaviour of barium and sodium in the sun, discussed by Russell, is explained when these additional factors are allowed for. The *causes of ionization* in stellar chromospheres are discussed. It is shown that while the density of radiation from the photosphere is incapable of giving rise to the hydrogen spectrum in A-type stars, electron collisions with hydrogen atoms will result in the observed effects. In view of some theoretical uncertainty in Saha's theory, a check hypothesis of *ionization by electron collisions* is formulated.

Physical Conditions in O-type Stars. From Saha's theory modified for the relative abundance of elements and independently from the electron collision hypothesis, the *temperature* of 9 Sagittæ is deduced from the disappearance of Mg-4481 to be in the mean 18,500°K. The temperatures of the two other O-type stars are determined from this temperature and those of the early B's by the use of the intensity ratios of certain pairs of lines. The temperature of 10 Lacertæ so deduced is 15,000° K, and of B.D. 35° 3930 N with considerable uncertainty as it is an extrapolation, is 22,000° K. Using these temperatures it is possible independently from the two ionization theories to determine the *relative abundance* of hydrogen and helium in these stars. It is found that while hydrogen has probably the same percentage abundance as in the first ten miles of the earth's crust, helium is probably 10^6 times more abundant. A simple physical interpretation of these facts is found when possible nuclear disintegration in deeper layers of the stars is considered.

Classification of Absorption Line O-type Stars. The Harvard class Oe5 is in practice distinguished from the classes Oe and Od by the absence of emission. This use of the presence or absence of an emission line as a criterion of type is shown to be inconsistent with the rest of the Harvard classification and physically unsound. Its use leads to the inclusion of the bulk of O-type stars in the class Oe5, though it is shown that from the intensities of absorption lines more than two-thirds of the stars so classified are earlier in type than Oe5. It is suggested that, as the absorption line O's form a continuous sequence with the B's the present Harvard symbols and their meanings be abandoned and the following decimal classification be substituted. Class Oo—Pickering lines disappeared; Class O5 (B.D. 35° 3930 N)—Ordinary helium disappeared; Class O7 (9 Sagittæ)—Mg 4481 missing; Class O9—Si III pair 4552, 4567 on the point of appearing. The coordinates, Harvard class, line intensities and proposed classes of 33 absorption line O's whose spectra have been secured here are given. The exclusion of the Wolf Rayet stars from the tentative scheme is justified.

INTRODUCTION

From their spectra it is evident that the atmospheres of O-type stars are in a highly ionized condition. This is shown by the appearance of the ζ Puppis series in these stars, the lines of which were first discovered by E. C. Pickering^{1*} in stellar spectra and were reproduced faintly in the laboratory under the most condensed discharge, by Fowler² some fifteen years later. The subsequent identification in O-type spectra of some enhanced carbon and oxygen lines produced under similar conditions of excitation pointed to a like conclusion, namely that the atoms in the atmospheres of these stars were highly ionized. The spectra of such stars, it may then be expected, will furnish a convenient method of studying the behaviour of ionized atoms, and also will give some information on the causes and the amount of ionization in the stellar atmospheres. It is with these aspects of O-type spectra that this paper is more particularly concerned.

The investigation had its origin in an attempt to discover in O-type stars the Pickering components to the Balmer lines. Shortly after Fowler's discovery of the Pickering lines and the two additional associated series in the laboratory, Dr. N. Bohr³ on the basis of his atomic theory stated that all these lines were due, not to hydrogen atoms as had formerly been believed, but to helium atoms which had permanently lost one electron. If his theory were correct he predicted that there should appear, some 2A to the violet of the Balmer lines, enhanced helium components which would form with the lines already

* References will be found at the end of Part I.

found by Pickering, a single series. From laboratory experiments Paschen⁴ showed in 1916 that these components existed. Clearly it was of importance, if only for the sake of completeness, to detect whether these components existed in stellar spectra; the more so as it would definitely show that the Pickering lines were due to enhanced helium. Preliminary experiments were initiated in 1920, and in 1921 sufficient evidence had been secured to justify an announcement⁵ of the discovery of these components. The next step was to determine with every accuracy the wave lengths of all the enhanced helium lines in these O-type stars. This in its turn involved a determination of the wave lengths of other stellar lines. The final result has been, after several extensions of scope, a discussion, as complete as possible, of the physical problems of O-type stars.

The arrangement of the paper is briefly as follows: *Part I* contains the necessary introductory material on the selection of stars, the instruments used, the observational data and the method of wave length determination. Essentially *Part II* is an application of stellar data to the problems of atomic structure. The evidence is given in detail for the existence of Bohr's predicted components, the value of the Rydberg constant for helium is computed, and from it are deduced stellar spectroscopic values of the mass of the electron and related universal constants. On the other hand *Part III* is an application of physical theories to the interpretation of the observed O-type spectra. After complete tables of the wave lengths of the lines in the three O-type stars are given, there follows an application of the methods developed in the Appendix in order to ascertain from the stellar spectra some of the physical conditions in the chromospheres of O-type stars. A practical astronomical result is a tentative revision of the Harvard classification for absorption line Class O stars. At the close of the paper is an *Appendix* in which is discussed the physical interpretation of stellar spectra. Two methods are there developed, one a slight modification of Saha's well known theory and the other an independent hypothesis of ionization by electron collision, which give independently either the stellar temperature or the relative abundance of the element from the disappearance of arc or spark lines in the spectrum of the star.

In writing the paper an attempt has been made to give, as the occasion for their use arises, a brief explanation of the various recent developments on atomic structure and origin of spectra. It is hoped, by thus reducing the labour of looking up references, that the value of the paper will be somewhat increased. In conclusion I would like to acknowledge the assistance rendered by my father, Dr. J. S. Plaskett, in particular, for the use of spectra taken by him in the course of his radial velocity programme, for his suggestions on the classification of O-type stars and for his patience and helpful discussions during a somewhat protracted investigation. Acknowledgment should also be made to Prof. E. H. Archibald of the University of British Columbia for the data he made available on recent determinations of the atomic weights of hydrogen and helium.

DOMINION ASTROPHYSICAL OBSERVATORY,

Victoria, B.C.,

July 24, 1922.

PART I—METHODS OF OBSERVATION

In this part of the paper are given details of the stars selected for observation, the instruments used and the observational data of the various plates. In the second section the method of wave length determination is explained.

SECTION 1—OBSERVATIONAL DATA

In view of the objects of the investigation three conditions determined the selection of stars for observation. First, the Pickering and Balmer lines had to be sharp enough to admit of the detection of components separated by less than 2Å. Second, the stars had to be bright to permit the use of high dispersion. And finally, it was desirable that the spectra should show as large a range in type as possible. The first two of these conditions eliminated the Wolf Rayet stars, and restricted observations to the absorption line O's, Harvard types Oe, Oe, Oe5. A preliminary examination in 1920 of the stars in

TABLE 1—O-TYPE STARS

Star	R.A. 1900		Dec. 1900		Vis. Mag.	Harv. Type	Remarks
	^h	^m	[°]	[']			
10 Lacertae	22	34.8	+38	32	4.91	Oe5	Sharp lines. He strong. 4481 Mg+ present. 4686 He+ sharp. Plate, fig. 1.
9 Sagittae	19	47.9	18	25	6.29	Oe5	Lines more diffuse. 4481 Mg+ disappeared. Fowler's N+ lines strong. Plate, fig. 2.
B.D. 35° 3930N	19	59.8	35	45	7.23	Oe	North component of Σ 2624, sep. 2" .He disappeared. He+ strong.

Miss Cannon's list⁶ and of 10 Lacertae, suggested by Frost,⁷ led to the selection of B.D. 35° 3930N and 10 Lacertae. Before any further work was done the Director, Dr. J. S. Plaskett, had commenced in 1921 observing O-type stars for radial velocity, using a very complete list of stars sent him by Miss Cannon. He suggested the inclusion of 9 Sagittae, a star which showed well defined Pickering lines. The positions, magnitudes, Harvard types and remarks on the spectra of these three stars are given in Table 1. Observations were confined to them, as it was felt that more information could be secured from their detailed study than from the same number of observations scattered over a greater number of stars.

Spectra were made with the universal spectroscope⁸ at the 108-foot focus of the 72-inch telescope. Four features in the design of the spectroscope may be noted,—(1) the mounting, (2) method of changing the dispersion, (3) the insertion of the comparison spectrum and (4) the temperature control. (1) All the optical parts of the spectroscope are enclosed

in a braced aluminium box, so that they form a single unit. This box is flexibly supported at two points in a frame which is attached to the telescope. The result is a great reduction in flexure when the telescope turns through large hour angles as in a long exposure. (2) The prisms are carried on a minimum deviation link work inside the aluminium box; each prism is held in a cell, which cell can be accurately replaced on the link work by virtue of two dowel pins. So well is this feature of the apparatus designed that it is possible to change from one to two or three-prisms, alter the angle of minimum deviation when necessary and make a focus test within an hour. Throughout the work the medium focus camera of 28 inches focal length was used, the focal length of the collimator being 45 inches. The resulting linear dispersions in A.U. per mm. are given in Table 2.

TABLE 2—LINEAR DISPERSION.

Prisms	Linear Dispersion, A.U. per mm.			
	H α	H β	H γ	H δ
I.....	122.90	45.16	29.34	23.22
II.....	66.10	23.42	14.34	10.92
III.....	45.33	16.56	9.26	6.62

(3) In order to insert the comparison spectrum two right angle prisms are held in position over the slit with a small aperture between them for the star image. The light from a 110 volt, 4 ampere D.C. iron arc is directed by a lens through several opal and ground glass screens on to the faces of these prisms, and thence on to the slit in the form of two limited patches on either side of the star image. The insertion of the opal glasses ensures that the collimator is filled. The advantage of this arrangement is that the comparison spectrum may be put on at intervals throughout the exposure without disturbing the slit or cutting off the light of the star. Comparisons were inserted at equal intervals at least three times, and upon occasion as many as ten times during the exposure. The only disadvantage of the arrangement is that the tips of the comparison lines are separated by approximately one-third of a mm. from the star spectrum, thus necessitating a correction for line curvature. (4) During the 1921 observations, over 80 per cent of the whole, the temperature in the spectroscope was kept constant, to about 1-20th degree centigrade by a Callendar Recorder.⁹ In 1920 the more usual mercury thermostat arrangement was used and gave satisfactory results.

In Table 3 are given details of the various spectra which were secured of 10 Lacertae, 9 Sagittae, B.D. 35° 3930N. The first column contains the G.M.T. of the exposure, the second the slit width, units being thousandths of an inch, the third column gives the dispersion, the fourth the region in focus on the plate, the fifth the brand of plate used—Seed 30 (fast,) Seed 23 (fine grain), Ilford Panchromatic, Ilford Panchromatic hyper-sensitized—, and the sixth contains the duration of exposure in hours and fractions.

TABLE 3—OBSERVATIONAL DATA

Date G.M.T.	Slit Width	Disp.	Region	Plate	Exp.	Date G.M.T.	Slit Width	Disp.	Region	Plate	Exp.
					hrs.						hrs.
<i>10 Lacertae</i>						1921 Sept. 29-80	1.6	I*	0.39—0.67 μ	I.P.h.	1.00
1920 June 19-97	1.2	I	0.39—0.49 μ	S 30	0.40	Oct. 1-65	2.0	III	0.53—0.67	I.P.h.	1.97
July 31-91	1.5	I	0.39—0.49	S 23	1.00	<i>9 Sagittae</i>					
Aug. 30-85	1.8	I	0.39—0.49	S 30	0.13	1921 July 14-79	2.0	I*	0.39—0.49	S 30	1.00
1921 July 26-96	2.0	I	0.39—0.67	I.P.	1.70	" 21-89	2.0	I*	0.39—0.49	S 30	0.47
Aug. 11-92	2.0	I*	0.39—0.49	S 23	0.37	Aug. 9-73	2.0	II	0.41—0.49	S 30	2.10
" 12-98	2.0	III	0.43—0.49	S 30	1.43	" 10-86	2.0	I*	0.39—0.49	S 30	0.60
" 26-86	2.0	II	0.41—0.49	S 23	1.33	" 12-82	2.0	III	0.43—0.49	S 23	6.00
" 26-91	2.0	II	0.41—0.49	S 23	1.00	" 26-75	2.0	II	0.41—0.49	S 23	4.00
Sept. 2-82	2.0	II	0.49—0.67	I.P.	7.50	Sept. 23-72	2.0	II	0.39—0.45	S 23	5.00
" 8-95	1.5	I*	0.39—0.49	S 23	0.33	<i>B.D. 35°3930 N</i>					
" 9-84	2.0	III	0.53—0.67	I.P.	9.50	1920 July 3-89	2.0	I	0.39—0.49	S 30	0.67
" 11-90	1.5	I*	0.39—0.67	I.P.	1.27	1921 Aug. 6-79	2.0	I	0.39—0.49	S 30	1.00
" 13-84	1.5	II	0.49—0.67	I.P.	9.73	" 11-79	2.0	I*	0.39—0.49	S 30	0.93
" 23-88	1.4	II	0.39—0.45	S 23	2.80	Sept. 8-77	2.0	I*	0.39—0.49	S 30	0.73
" 28-69	1.4	II	0.39—0.45	S 23	3.50						

*Spectra taken by J. S. Plaskett.

The following additional comments may be made. In *10 Lacertae* the only difficulty lay in securing high dispersion spectra in the region 0.49 — 0.67 μ . Such spectra were essential in order to detect the component to $H\alpha$,—in view of the diffuseness of the lines and the small linear dispersion at $H\alpha$ with I-Prism (see Table 2). With Ilford Panchromatic Plates and II or III-Prism dispersion, as Table 3 shows, exposures of the order of eight hours were necessary. The unavoidable flexure of the spectroscope in these long exposures resulted in spectra that were not of the best definition. Some experiments were tried with hypersensitizing the Panchromatic Plates with an ammonia bath.¹⁰ Though the exposures in this way were reduced to less than one-third of their former value, the plates unfortunately showed reticulation and it was not until after several failures that a moderately satisfactory plate was obtained. In neither *9 Sagittae* nor *B.D. 35°3930N* were spectra in the red secured, though two unsuccessful attempts were made in the case of *9 Sagittae*. Spectra of *B.D. 35°3930N* were difficult to obtain, in so far as seeing conditions much above the average were required to separate it clearly from its southern component. A number of the I-Prism plates of the three stars were taken by Dr. J. S. Plaskett in the course of his radial velocity programme of O-type stars. These are denoted in the table by asterisks. Only three out of the ten *9 Sagittae* plates of J. S. Plaskett were included,—namely those which, by inspection with an eyepiece, clearly showed the presence of the Pickering component to $H\gamma$.

SECTION 2—METHOD OF WAVE LENGTH MEASUREMENT

The plates, secured as detailed in Table 3, were measured on the Gaertner machine. In addition all II and III-Prism plates and all I-Prism panchromatic plates were re-measured after an interval of two weeks or longer on the Toeffer machine. The plates

were measured red right and red left, iron arc comparison lines and stellar lines being measured as they occurred. Four settings were made on each line except in the case of the Pickering lines when as a rule, because of their diffuseness, eight settings were made. Each measure was reduced separately to determine the wave lengths. Three stages in this determination may be distinguished:—(1) the preliminary reductions, (2) the correction for curvature and (3) the correction for velocity. These may be considered in turn.

Preliminary Reductions. Using Burn's¹¹ wave lengths in I.A. of the lines in the iron arc comparison spectrum, the Hartmann constants were computed for each measure of a plate from three of these iron arc lines. From these constants the measures of comparison lines and stellar lines in mm. were converted into wave lengths. As the Hartmann formula does not hold accurately, the residuals (Burn's λ — computed λ) were formed for each comparison line and a curve of errors was drawn. From this curve the corrections for each stellar wave length were read off and applied.

Curvature Correction. Owing to the fact, as pointed out in sec. 1, that the tips of the comparison lines are separated by 0.3 mm. from the star spectrum, there must be applied to these computed wave lengths a correction for curavture. The curvature of the spectral lines results in a displacement to the red of the stellar lines relative to the comparison lines by an amount which is no simple function of the wave length. In order to determine the value of this correction the following procedure was adopted. A series of exposures

TABLE 4—CURVATURE CORRECTIONS.

λ	I-Prism	II-Prism	III-Prism	λ	I-Prism	II-Prism	III-Prism
4000	-0.007A	-0.008A		5500	-0.024A	-0.030A	-0.025A
4300	.011	.013	-0.010A	5800	.028	.035	.028
4600	.014	.017	.014	6100	.031	.039	.032
4900	.018	.022	.018	6400	.035	.044	.036
5200	.021	.026	.021	6700	-0.038	-0.048	-0.039

was made with each of the three dispersions, the whole length of the slit being exposed to the light of the comparison arc. The curvature of some eight or more lines in the length of the spectrum from 3900—6700 were determined from measures of six points in each line. The curves were assumed, as is customary, to be parabolas, and a series of least-square solutions were run through to determine the constants for each line. From the constants the value of the correction in A.U. to be applied to a stellar line at the given wave length could readily be determined. As the value of these corrections were known for at least eight wave lengths through the spectrum, a curve could be drawn through these points for each dispersion. From these curves were read off the corrections to be applied to a stellar line at any wave length and for any dispersion. A shortened list of these corrections appears in Table 4. It is to be noted that even if these corrections are not absolutely accurate but are relatively accurate along the length of the spectrum, the resulting wave lengths, after the velocity correction is applied, will be correct.

Velocity Correction. The stellar wave lengths as so far obtained still differ from their true values by reason of the relative velocity of the star and the observer,—the Doppler effect. This causes a displacement, $\Delta \lambda$, in the stellar lines where $\Delta \lambda = \frac{v}{c} \cdot \lambda$, v being the relative velocity of star and observer and c the velocity of light. In order to eliminate this displacement certain standard velocity lines are selected, the value of $\Delta \lambda$ (star—laboratory) is determined and v is computed for each line. The weighted mean of these velocities is then used to recompute $\Delta \lambda$ for each stellar line. The correction is applied with the proper sign, and the resultant wave lengths are the true values in the star.

The selection of these velocity standards is most important as it is here that the chances of introducing systematic error are greatest. The following criteria were applied. (1) The lines must have good laboratory wave lengths, preferably determined from interferometer measures or based on Burn's tertiary iron arc standards. (2) The lines in the star must be sharp and readily measurable. (3) The lines must not be likely to be blended with other known lines. Following these criteria the list of lines in Table 5 was drawn up for each star. The first column contains the laboratory wave length in I.A., the second the source and the third the authority, the numbers in this column referring to references at the bottom of the table. The fourth column shows the number of measures in which the line was used as a velocity standard, and the fifth column is the mean weight assigned to the line.

TABLE 5—VELOCITY STANDARDS

λ (I.A.)	Origin	Authority	Used	Mean Wt.	λ (I.A.)	Origin	Authority	Used	Mean Wt.	λ (I.A.)	Origin	Authority	Used	Mean Wt.
<i>10 Lacertae</i>					4471.477	He	1	18	6.2	4340.467	H	4	10	5.1
3964.727	He	1	6	2.3	4481.195	Mg	5	8	1.2	4387.928	He	1	5	2.1
4072.156	On	2	5	1.0	4510.91	N	3	7	1.3	4471.477	He	1	11	6.2
4075.869	On	2	10	1.3	4514.865	N	3	8	1.2	4510.91	N+	3	6	2.0
4097.327	N	3	16	4.1	4713.143	He	1	10	3.1	4514.865	N	3	7	1.6
4101.738	H	4	12	6.6	4861.326	H	4	5	5.0	4634.165	N	3	3	1.0
4103.393	N+	3	12	2.2	4921.929	He	1	8	3.0	4640.649	N+	3	3	1.0
4119.222	On	2	4	1.0	5015.675	He	1	5	2.8	4713.143	He	1	4	3.2
4120.812	He	1	16	2.2	5592.35	On	6	8	1.0	4921.929	He	1	1	3.0
4143.759	He	1	15	2.2	5875.618	He	1	8	6.6					
4319.647	On	2	3	1.0	6562.793	H	4	3	6.7	<i>B.D. 35° 3930.V</i>				
4340.467	H	4	13	6.5	6678.149	He	1	8	2.9	4101.738	H	4	2	4
4349.435	On	2	10	1.5						4340.467	H	4	3	4
4366.906	On	2	3	1.0	<i>9 Sagittae</i>					4634.165	N+	3	4	1
4387.928	He	1	20	3.9	4097.327	N	3	4	4.2	4640.649	N	3	4	1

<i>Authorities</i>	1—	P. W. Merrill	—	Bureau of Standards, Scientific Paper, No. 302, 1917.
	2—	J. S. Clark	—	Astrophysical Journal, 40, 332, 1914.
	3—	A. Fowler	—	Monthly Notices, R.A.S., 80, 692, 1920.
	4—	W. E. Curtis	—	Proc. Royal Society A, 90, 605; 96, 147.
	5—	A. Fowler	—	Phil. Trans. Roy. Soc. A, 214, 225, 1914.
	6—	A. Fowler	—	Monthly Notices, R.A.S., 77, 511, 1917.

The following comments may be made on these velocity standards. No ionized helium lines were used as velocity standards as it was desired to determine their wave lengths independently of any previous determinations. The hydrogen lines were only used as standards when the Pickering components could be measured,—otherwise the measured Balmer line would be a blend. In *10 Lacertae* the He line 4026 was not used as a standard as it is blended with a Pickering line in the same position. The enhanced nitrogen lines 4379, 4523 were not included because they were poorly defined and difficult to measure. A number of oxygen lines are included as standards, but have uniformly been given low weight as compared with the stronger and better defined lines of other elements. In *9 Sagittae*, as the table shows, there are fewer velocity standards, and this has of necessity meant that the correction for velocity in the individual measures is not so good as it is in *10 Lacertae*. Clearly, however, it is preferable to depend upon a few good lines of accurate wave length which are free from blends, than it is to use a greater number of lines of inferior quality. If this latter procedure be adopted the chances of systematic error are great. The use of few velocity standards will, at the worst, only introduce an accidental error which in the mean will be eliminated. For *B. D. 35° 3930N*, as well as for *9 Sagittae*, the enhanced nitrogen lines 4634·165, 4640·649 appear as emission and have only been given unit weight in determining the velocity correction. On the whole it is felt that the lines selected form a homogeneous group, and that the mean stellar wave lengths of a number of measures which result from their use should be free from avoidable systematic error.

A by-product of the correction for velocity is of course the velocities of the stars themselves. These velocities, corrected to the sun¹², are given in Table 6. For *10 Lacertae* the individual velocities are probably worthy of some confidence as they depend upon the use of a large number of velocity standards. Exceptions to this are the pan-chromatic plates with higher dispersion, in which only three or four velocity standards have been used. In these cases the velocity is of doubtful value. Omitting these cases, denoted by a P, it appears probable that *10 Lacertae* has a constant radial velocity of -10.1 ± 0.4 km. In the case of *9 Sagittae* the use of a few velocity standards for each

TABLE 6—RADIAL VELOCITIES OF O-TYPE STARS

Date G.M.T.	Disp.	Rad. Vel.	Date G.M.T.	Disp.	Rad. Vel.	Date G.M.T.	Disp.	Rad. Vel.
<i>10 Lacertae</i>			Sept. 9·84	III P	-19·0	Aug. 10·86	I	+ 3·6
1920 June 19·97	I	- 6·4	" 11·90	I	-11·1	" 12·82	III	+11·2
July 31·91	I	- 8·0	" 13·84	II P	-10·4	" 26·75	II	+11·8
Aug. 30·85	I	-10·1	" 23·88	II	-14·4	Sept. 23·72	II	+ 4·8
1921 July 26·96	I	-11·1	" 28·69	II	-11·7			
Aug. 11·92	I	- 9·8	" 29·80	-I	- 9·2	<i>B. D. 35° 3930 N</i>		
" 12·98	III	- 8·1	Oct. 1·65	III P	-12·0	1920 July 3·89	I	+ 9
" 26·86	II	- 8·1	<i>9 Sagittae</i>			1921 Aug. 6·79	I	-19
" 26·91	II	-12·3	1921 July 14·39	I	+17·5	" 11·79	I	- 6
Sept. 2·82	II P	- 2·2	" 21·89	I	+ 2·2	Sept. 8·77	I	- 1
" 8·95	I	-10·5	Aug. 9·73	II	+27·1			

measure makes it difficult to decide whether the star has a constant velocity, or is a spectroscopic binary. J. S. Plaskett, from his measures of a number of single-prism plates using a large number of velocity standards, has concluded that the star has a constant velocity. From Table 6 its mean velocity would be $+11.2 \pm 2.3$ km. Little can be concluded from the radial velocities for B. D. 35° 3930N. In view of the poor quality of the lines and the fact that as a rule only three velocity standards could be used, the range is no larger than would be given by a constant velocity star. From the measures the velocity would be -4 km.

In conclusion the following points on the method of wave length determination may be noted. The computations were carried through to the thousandth of an A.U. but after the application of the velocity correction the wave lengths were shortened to hundredths. Throughout wave lengths expressed in I.A. have been used so that the resulting stellar wave lengths will also be in this scale. The various computations have been checked several times, and every effort has been made to eliminate possible systematic error. As a consequence, some confidence is felt that the resulting mean wave lengths are as accurate as can be expected from stellar spectra with somewhat ill-defined lines.

REFERENCES TO THE INTRODUCTION AND PART I

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PART II—BOHR'S HELIUM LINES AND THE MASS OF THE ELECTRON

In this part of the paper are treated applications of astronomical measurement to theories of atomic structure and to the determination of the values of atomic constants. In the first section, after a theoretical introduction, the evidence is given in detail for the existence of Bohr's predicted Pickering components to the Balmer lines in O-type spectra. In the next section the mean wave lengths of the ionized helium lines in 10 Lacertæ and 9 Sagittæ are used to determine the value of N_2 , Rydberg's constant for helium. From this value of N_2 and from Birge's recomputed value of N_1 for hydrogen, the spectroscopic values of the electron mass and other universal constants are determined in the final section.

SECTION 3—EVIDENCE FOR THE PICKERING COMPONENTS IN O-TYPE STARS

Bohr^{1*} formulated his theory for the purpose of explaining the spectrum of an element in terms of the structure of its atom. He considered the case of a single electron (charge $-e$, mass m_0) and a nucleus (charge E , mass M) revolving in circle orbits about their common centre of gravity. By assuming,—(1) that the combined angular momentum of electron and nucleus was only equal to $nh/2\pi$ where $n = 1, 2, 3 \dots$ and h is Planck's constant; and by assuming,—(2) that losses of energy in the atomic system occasioned by the shrinkage of electron and nucleus to inner orbits appeared as monochromatic frequency, $\nu = \Delta W/h$ where ΔW is the loss of atomic energy, Bohr found that the formula for spectral emission was

$$\nu = \frac{2\pi^2 m_0 e^4}{h^3 (1 + m_0/M)} \cdot \left(\frac{E}{e}\right)^2 \left(\frac{1}{n^2} - \frac{1}{m^2}\right) = N \left(\frac{E}{e}\right)^2 \left(\frac{1}{n^2} - \frac{1}{m^2}\right) \dots (1)$$

In this formula m is the quantum number of the initial orbits, n the quantum number of the orbits into which the electron and nucleus fall, and N , if the known values of m_0 , e , h be substituted, turns out within the limits of error of m_0 , e , h to be the Rydberg constant. For hydrogen, $E = +e$, (1) is then the formula for the Lyman series when $n = 1$, $m = 2, 3, 4 \dots$, for the Balmer series when $n = 2$, $m = 3, 4, 5 \dots$, and for the Paschen series when $n = 3$, $m = 4, 5, 6 \dots$. The physical interpretation of the formula in the case of the Balmer series is that $H\alpha$ is given by atoms in which the electron is falling from the three to the two quantum orbit, $H\beta$ by atoms in which the electron is falling from the four to the two quantum orbit and so on. For ionized helium atoms (atoms which have permanently lost one of their two electrons) (1) then becomes, for $n = 3$, $m = 4, 5, 6 \dots$, the formula for the complete 4686 series found by Fowler² in the laboratory. The case when $n = 4$ is $\nu = 4 N_2 \left(\frac{1}{4^2} - \frac{1}{m^2}\right)$, where $m = 5, 6, 7 \dots$, is the complete Pickering series. Odd values of m give the lines 5411, 4541, 4200, etc., found by Pickering³ in ζ Puppis, and even values give lines close to but not coincident with the Balmer lines, since N_2 (helium) = $N_1 \left[\frac{1 + m_0/m_1}{1 + m_0/4m_1}\right]$ approx. = $1.000407 N_1$ approx. where N_1 is the constant for hydrogen and m_1 is mass of hydrogen nucleus. Actually these additional Pickering lines should lie between 1 and 3 Å to the violet of the Balmer lines.

*References at the end of Part II.

Evidently the discovery of these predicted Pickering components would furnish a most important verification of Bohr's theory. In the laboratory Evans ⁴ has been partially and Paschen⁵ completely successful in isolating them. In stellar spectra the difficulty lies in the diffuseness of the Pickering lines, so that increase of dispersion only tends to weaken and widen without helping to separate them from the Balmer lines. Accordingly the most important factor in the detection of the components is the selection of stars with comparatively sharp Pickering lines; such in fact are the stars 10 Lacertæ, 9 Sagittæ and B.D. 35° 3930 N. The existence of the components in these stars will be most clearly shown by giving detailed tables of the individual wave lengths for each measure of the three stars.

The detailed measures for **10 Lacertæ** are given in Table 7. The first column contains the date on which the plate was taken, and the second the dispersion which is indicated by the numerals I, II, III (see Table 2),—the letters T or G following these numerals indicate on which machine, Toepfer or Gaertner, the plate was measured. The succeeding columns are for $H\alpha$, its $He+$ component, a line of unknown origin at $\lambda 6558$, the $He+$ line $\lambda 5411$, $H\beta$, its $He+$ component, the $He+$ line $\lambda 4686$, the $He+$ line $\lambda 4541$, $H\gamma$, its $He+$ component, a $Ti+$ line $\lambda 4338$, the $He+$ line $\lambda 4200$, the $N+$ line $\lambda 4103$, $H\delta$ and its $He+$ component. In the columns themselves only units and fractions of an A.U. are given, the first three figures of the wave length being given at the head of each column. At the foot of each column is given the simple mean of the wave lengths, the probable error of the mean and the estimated intensity of the line. The following comments may be made on the individual lines in the table.

$H\alpha$. The detection of the Pickering component to $H\alpha$ is made difficult for three reasons:—(1) the low linear dispersion, not greater than 45 A.U. to the mm. at $H\alpha$ (see Table 2), (2) the flexure introduced by long exposures, and (3) the presence of a line of unknown origin at $\lambda 6558$. Nevertheless on one each of the measures of the three high dispersion plates which could be used at $H\alpha$, a component has been set on with mean wave length $6560\cdot04$. When this component has not been seen, in two of the three cases the measures of $H\alpha$ are shifted $0\cdot6$ A to the violet showing that a blend of $H\alpha$ and its $He+$ component has been measured. It seems probable, therefore, that the predicted Pickering component to $H\alpha$ is present.

$He+ 5411$. This line is not easy to measure as it is very ill-defined.

$H\beta$. A component to $H\beta$ is readily seen on all the high dispersion spectra. Fig. 3 of the Plate is a reproduction of $H\beta$ and its component from the III-prism spectrum of Aug. 12·98. In four out of the six cases, where $H\beta$ has been measured, the wave length of the component has been determined. Its mean wave length, $4859\cdot08$, and its abnormally high intensity, compared with 5411 and 4541, point to a probable blend of $He+$ (Paschen's $\lambda 4859\cdot34$) and $N+$ (Fowler's $\lambda 4858\cdot82$). Lines of enhanced nitrogen are very common in 10 Lacertæ as Table 13, Part III, shows.

TABLE 7—WAVE LENGTHS (Å.) OF H, He⁺ AND OTHER LINES IN 10 LACERTÆ

Date	Disp.	H α 656—	He ⁺ 656—	— 655—	He ⁺ 541—	H β 486—	He ⁺ 485—	He ⁺ 468—	He ⁺ 454—	H γ 434—	He ⁺ 433—	Ti ⁺ 433—	He ⁺ 420—	N ⁺ 410—	H δ 410—	He ⁺ 410—
1920 June 19-97	IG	.....	.....	.....	.....	1.31	.....	5.63	1.90	0.31	.....	7.81	0.28	3.45	1.66	0.15
July 31-91	IG	.....	.....	.....	.....	.....	.....	.....	1.74	0.39	.....	7.64	9.62	.....	.....	.....
Aug. 30-85	IG	.....	.....	.....	.....	.....	.....	.....	.....	0.58	9.12	.....	9.65	3.18	1.72	0.59
1921 July 26-96	IT	.....	.....	.....	2.16	.....	.....	5.70	1.69	.....	.....	.....	0.17	.....	.....	.....
	IG	.....	.....	.....	1.91	.....	.....	5.69	1.74	0.23	.....	7.88	9.99	.....	.....	.....
Aug. 11-92	IG	.....	.....	.....	.....	.....	.....	.....	.....	0.32	.....	7.78	9.48	.....	.....	.....
Aug. 12-98	IIIT	.....	.....	.....	.....	1.33	8.82	5.73	1.68	0.35	8.41	.....	.....	.....	.....	.....
	IIIG	.....	.....	.....	.....	1.35	8.90	5.63	1.59	0.32	8.50	.....	.....	.....	.....	.....
Aug. 26-86	IIT	.....	.....	.....	.....	1.34	.....	5.69	1.73	0.39	8.90	.....	0.19	3.31	1.73	0.37
	IIG	.....	.....	.....	.....	.....	.....	5.72	1.82	0.41	9.05	.....	0.21	3.31	1.76	0.43
Aug. 26-91	IIT	.....	.....	.....	.....	1.32	9.18	5.75	1.77	0.50	9.12	.....	0.01	.....	.....	.....
	IIG	.....	.....	.....	.....	1.30	9.40	5.73	1.72	0.42	8.88	.....	0.07	3.33	1.69	0.48
Sept. 2-82	IIT	2.66	.....	8.20	1.41	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
	IIG	2.68	0.02	8.04	1.15	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
Sept. 8-95	IG	.....	.....	.....	.....	.....	.....	5.77	1.50	.....	.....	.....	.....	3.31	1.72	0.27
Sept. 9-84	IIIT	2.46	0.09	8.63	1.62	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
	IIIG	1.98	.....	8.16	1.43	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
Sept. 11-90	IT	.....	.....	.....	1.80	.....	.....	.....	1.32	.....	.....	.....	0.12	3.38	1.69	9.93
	IG	.....	.....	.....	1.46	.....	.....	.....	1.18	0.54	8.84	7.68	0.19	3.23	1.70	9.98
Sept. 13-84	IIT	.....	.....	.....	1.61	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
	IIG	.....	.....	.....	1.60	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
Sept. 23-88	IIT	.....	.....	.....	.....	.....	.....	.....	.....	0.16	8.49	.....	.....	.....	.....	.....
Sept. 28-69	IIT	.....	.....	.....	.....	.....	.....	.....	.....	0.41	9.07	.....	0.19	3.36	1.74	0.61
	IIG	.....	.....	.....	.....	.....	.....	.....	.....	0.46	9.26	.....	0.17	3.39	1.73	0.61
Sept. 29-80	IT	.....	.....	.....	1.73	.....	.....	.....	1.33	0.48	8.73	.....	0.27	3.39	1.70	9.70
	IG	.....	.....	.....	1.54	.....	.....	.....	.....	0.37	8.96	.....	0.34	3.26	1.77	0.11
Oct. 1-65	IIIT	2.00	.....	8.43	1.44	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
	IIIG	2.62	0.01	8.04	1.72	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
Means:—		2.51	0.04	8.25	1.62	1.32	9.08	5.70	1.62	0.42	8.87	7.76	0.06	3.32	1.72	0.27
Prob. Errors:—		±.04	±.02	±.06	±.04	±.01	±.09	±.01	±.04	±.02	±.05	±.03	±.04	±.01	±.01	±.06
Intensities:—		10	3	4	4	10	5	9	3	9	2	2	2	3	9	2

He⁺ 4686. This line is one of the best in the spectrum; it is very sharp and the measures are accordant. The mean wave length of 4685.70 may be compared with Fowler's² laboratory value of 4685.80, Frost's⁶ 10 Lacertæ value of 4685.72, and Paschen's⁵ wave length (the computed centre of gravity from his value of N₂) of 4685.74.

He⁺ 4541. This is the usual diffuse line of the Pickering series.

H γ . Though not easy to see with a low power magnifier, the Pickering component has been seen and measured in 13 out of 17 measures of H γ . Furthermore, in the cases in which it has not been measured, the mean wave length of H γ — 4340.31, as compared with 4340.42 in cases where the component has been measured, shows that a blend of H γ and its He⁺ component has probably been set on. On 5 I-prism plates a Ti⁺ line at 4338 has also been measured, but in only one of these measures have H γ , its He⁺ component and the Ti⁺ line been seen. It is curious that the Ti⁺ line has never been measured on higher dispersion plates, and it is probable that the line is of low central intensity and diffuse, so that increase of dispersion "washes it out."

He+ 4200. This line is not easy to measure as it is diffuse and ragged. From its mean wave length 4200·06 it is probable that it is composed almost entirely of *N+* 4200·06.

Hδ. The *He+* component has been measured most easily on I-prism plates in which the dispersion of 23 Å to the mm. seems to be of the right order for separation, without widening the line too greatly. A reproduction from the I-prism plate of Sept. 11·90 of the group *N+* 4103, *Hδ* 4102, *He+* 4100 is given in fig. 4 of the Plate. No attempt was made to measure the *He+* component unless the *N+* line to the red of *Hδ* was clearly visible. The mean of 12 measures gives a wave length of 4100·27 which, when compared with Paschen's value 4100·05, would seem to indicate a blend. It is noteworthy, however, that in the plate of best definition, I-prism Sept. 11, the wave length 4099·96 is in close agreement with Paschen.

Summarizing, the evidence for 10 Lacertae definitely indicates the presence of components near the predicted and laboratory positions for *Hβ*, *Hγ*, *Hδ*. For *Hα* the evidence is not so good, but, in view of the low linear dispersion and the difficulty of measurement, there can be little doubt that the component is there.

The detailed measures for 9 Sagittae are given in Table 8. This table is of precisely the same form as that for 10 Lacertae, the successive columns after the date and dispersion giving the wave lengths for the individual measures of *Hβ*, a *N+* component, the Pickering line at λ4541, *Hγ*, its *He+* component and measures in the neighbourhood of *Hδ*.

TABLE 8—WAVE LENGTHS (Å.) OF *H*, *He+*, *N+* IN 9 SAGITTAE

Date	Disp.	<i>Hβ</i> 468—	<i>N+</i> 485—	<i>He+</i> 454—	<i>Hγ</i> 434—	<i>He+</i> 433—	<i>He+</i> 420—	<i>N+</i> 410—	<i>Hδ</i> 410—	<i>He+</i> 410—
1921 July 14·79.....	I G	.....	.....	1·48	0·62	8·43	0·07	.....	.....	.....
July 21·89.....	I G	.....	.....	2·07	0·30	8·52	0·30	.....	.....	.....
Aug. 9·73.....	II T	0·83	8·83	1·62	0·49	8·24	9·69	.....	.....	.....
	II G	.....	.....	1·65	0·54	8·61	9·85	.....	.....	.....
Aug. 10·86.....	I G	.....	.....	2·06	.....	.....	0·40	.....	.....	.....
Aug. 12·82.....	III T	.....	.....	1·52	0·66	9·36	.....	.....	.....	.....
	III G	.....	.....	.....	0·61	9·15	.....	.....	.....	.....
Aug. 26·75.....	II T	0·66	8·23	1·87	0·40	8·45	9·86	.....	.....	.....
	II G	0·74	8·41	1·84	0·36	8·85	0·07	3·19	1·84	0·77
Sept. 23·72.....	II T	.....	.....	.....	0·20	8·64	0·20	3·66	2·20	1·03
	II G	.....	.....	.....	0·30	8·86	0·24	3·73	2·11	0·70
Means:	.....	0·74	8·49	1·76	0·45	8·71	0·08	3·53	2·05	0·83
Prob. Errors	.....	±·03	±·12	±·05	±·03	±·07	±·05	±·12	±·07	±·07
Intensities	.....	9	4	6	9	4	4	5	8	4

The means, probable errors of means and estimated intensities of the lines appear at the foot of each column. The following comments may be made on the table.

Hβ. The *He+* component has not been measured separately, but the mean wave length of *Hβ* — 4860·74, displaced 0·6 Å to the violet of its laboratory wave length, suggests very strongly that a blend of *Hβ* and its *He+* component has been measured.

He+ 4541. The line is well defined and the large accidental error is probably a result of the enforced use of comparatively few velocity standards (see sec. 2).

$H\gamma$. The $He+$ component is readily seen on high dispersion plates with a low power magnifier. Fig. 5 of the Plate is a reproduction of $H\gamma$ and its $He+$ component from the III-prism spectrum of Aug. 12.82. The component has been measured on all the plates with the exception of one, and the mean wave length $\lambda 4338.71$ is in good accord with Paschen's laboratory value of $\lambda 4338.69$.

$He+ 4200$. As in 10 Lacertae this line is probably composed largely of $N+ 4200.06$.

$H\delta$. $N+ 4103$, $H\delta 4102$, $He+ 4100$ all run into one another to form a wide fuzzy blend, as may be seen from the Plate, fig. 2. An attempt was made to measure the three components in the last three measures but without any marked success.

Summarizing, it is evident that in 9 Sagittae there is a component in the correct position for $H\gamma$, probably a component to $H\beta$ and doubtfully to $H\delta$.

The detailed measures for B.D. $35^\circ 3930$ N appear in Table 9 which is identical in form with Tables 7 and 8 for 10 Lacertae and 9 Sagittae. The probable errors of the means are not given, and the wave lengths are only carried to tenths of A.U. The

TABLE 9 -WAVE LENGTHS (A.) OF H, $He+$, $N+$ IN B.D. $35^\circ 3930$ N

Date		Disp.	$H\beta$	$N+$	$He+$	$He+$	$H\gamma$	$He+$	$He+$	$H\delta$	$He+$	$He+$
			468—	485—	468—	454—	434—	433—	419—	410—	410—	402—
1920 July	3.89	I G	0.8	7.7	6.1	0.8	0.5	8.5	9.8	1.8	0.2	5.5
1921 Aug.	6.79	I G	1.3	8.0	7.2	1.7	0.4	8.3	9.8	1.9	0.2	6.3
Aug.	11.79	I G	0.9	8.5	7.4	1.3	9.4	.....	0.0	0.7	.....	5.2
Sept.	8.77	I G	.....	.....	7.5	1.2	0.6	8.6	9.8	.....	.....	.....
Means:—			1.0	8.1	7.0	1.2	0.5	8.5	9.8	1.8	0.2	5.7
Intensities:—			9	1	80 E	7	9	6	6	9	6	2

difficulty with this star, as already indicated in sec. 2, is that at the most there are only four velocity standards available, two of which are emission lines, and furthermore that the line character is exceedingly poor. The following comments may be made.

$H\beta$. It is possible that the measured wave length is a blend of $H\beta$ and its $He+$ component, as the mean wave length is displaced 0.3 A to the violet of the laboratory position of $H\beta$.

$He+ 4686$. This line is a very strong emission band, sometimes as wide as 10 A. The measures of its centre are uncertain.

$He+ 4541$. This line was very ragged and the measures were difficult to make. It will be noted that it is comparable in intensity with the Balmer lines.

$H\gamma$. This line and its Pickering component were measured separately in three out of four cases; the remaining case a blend of the two was measured.

$He+ 4199$. As the wave length shows, this line in B.D. $35^\circ 3930$ N is probably composed largely of $He+$.

$H\delta$. This line and its Pickering component have been measured separately twice, and on the third occasion a blend of the two was measured.

$\text{He+ } 4025$. B.D. 35° 3930 N shows possibly just a trace of ordinary He at 4471. Consequently this line will be composed almost entirely of He+ . Its mean wave length 4025.7 is in good agreement with the centre of gravity of the line computed from Paschen's value of N_2 , viz. $\lambda 4025.63$.

Summarizing again, it is evident that, in B.D. 35° 3930 N there are components at the predicted positions and with the correct intensities for $\text{H}\gamma$ and $\text{H}\delta$, and there is possibly a suspicion of a component to $\text{H}\beta$.

Reviewing all the evidence there can be little doubt that the Pickering components to the Balmer lines, as predicted by Bohr, are present in O-type stars. The fact that they have been measured on so many plates of a given star puts out of court the possibility that plate flaws have been set on. On the other hand, the accordance of the intensities of the components and the members of the original Pickering series in the three stars makes it probable that the two sets of lines are related. Further if the components had only been measured in one star, or even in any number of stars of the same spectral type, it would be legitimate to suppose that the observed components were due to some other element, though the fact that they are obtained for four members of the Balmer series in 10 *Lacertæ* would make such a hypothesis doubtful. But when components have been measured in the predicted positions and with the correct intensities in stars which differ widely in type (see sec. 7 and 8), it is highly probable that such components are those predicted by Bohr and observed by Paschen in the laboratory.

TABLE 10—MEAN WAVE LENGTHS (Å.) OF H AND He+

Stellar Wave Lengths						Laboratory Wave Lengths	
Hydrogen			Enhanced Helium			H	He+
λ	No. Me.	p. e.	λ	No. Me.	p. e.		
6562.59	3	$\pm .04$	6560.04	3	$\pm .02$	6562.793	6560.13
			5411.62	14	.04		5411.55
4861.32	4	.01	4859.08†	4	.09	4861.326	4859.34
			4685.70	10	.01		4685.74
			4541.67*	22	.03		4541.61
4340.43*	23	.02	4338.80*	23	.04	4340.467	4338.69
			4200.06†	25	.03		4199.86
4101.72	12	.01	4100.27	12	.06	4101.738	4100.05

*Mean of all the 10 *Lacertæ* and 9 *Sagittæ* measures. Unstarred $\lambda\lambda$'s are means of 10 *Lacertæ* measures alone.

†Blends with enhanced nitrogen.

In Table 10 the mean stellar wave lengths of the hydrogen and enhanced helium lines are compared with the laboratory values of Curtis⁷ for hydrogen and of Paschen⁵ for ionized helium. The details of the table are self explanatory, but some comment is required on the method of forming the means. In view of the paucity of velocity standards and the poor character of the lines, the wave lengths of B.D. 35° 3930 N have not

been included in the means. Of the eight enhanced helium lines in the table only three, denoted by asterisks, are means of the measures of both 10 Lacertæ and 9 Sagittæ; the remaining five are means from 10 Lacertæ alone. While a wave length of 4100 was available from 9 Sagittæ, it was not included since the measurement was, as previously noted, a matter of guess work. In forming the means in Table 10 each individual measure, as set forth in Tables 7 and 8 for 10 Lacertæ and 9 Sagittæ respectively, has been given unit weight. This actually results in giving more weight to II- and III-prism plates (since they are measured in duplicate), and more weight to the wave lengths of 10 Lacertæ than of 9 Sagittæ (since there are nearly twice as many measures of 10 Lacertæ available in the region common to both than there are of 9 Sagittæ). In short, the procedure adopted automatically assigns the weights that theory would prescribe, viz.—high dispersion plates and those with the greater number of velocity standards to be given the greater weight (compare sec. 2). Referring to the table it will be noted that, with the exception of $H\alpha$ which is very difficult to measure, the wave lengths of the Balmer lines in the stars agree with Curtis' values almost within the probable errors of the mean stellar values. The discrepancies between the stellar wave lengths of the enhanced helium lines and Paschen's laboratory values of the same, in the final column of Table 10, are more marked, but are not extraordinary when the poor character of the stellar lines is considered.

SECTION 4—VALUE OF THE RYDBERG CONSTANT, N_2 , FOR HELIUM

The Rydberg constant N in the formula $\nu = N \left(\frac{E}{e}\right)^2 \left(\frac{1}{n^2} - \frac{1}{m^2}\right)$, as was shown in the early part of sec. 3, has the value

$$N = \frac{2\pi^2 m_0 e^4}{h^3 (1 + m_0/M)} \dots \dots (2)$$

It was also pointed out in sec. 3, that if the known values of m_0 , e , h were substituted, the values of the computed and the spectroscopically determined constants agreed within the limits of the errors of m_0 , e , h . Now clearly this process may be reversed, and the value of N , derived from spectroscopic observations, may be used to compute the values of m_0 , e , h . In this section it is proposed to use the mean stellar wave lengths of the enhanced helium lines, as given in Table 10, to compute spectroscopically the value of N_2 , the Rydberg constant for helium. In the following section this value of N_2 will be used to compute the universal constants m_0 , h and so on.

In determining the value of N spectroscopically, the simple Bohr formula for the frequency of the lines, has to be modified to allow for the relativistic variation in mass of the electron. The complete theory is due to Sommerfeld³, and only the necessary formulæ will be summarized here. Removing the restriction that the electron and nucleus must revolve in circular orbits, and "quantizing" with respect to radial as well as angular momentum, Sommerfeld has found that the 1 quantum orbit will be a circle, the 2 quantum orbit a circle or an ellipse of eccentricity $\sqrt{3/2}$, the 3 quantum orbit a circle or one of two ellipses of eccentricities $\sqrt{5/3}$, $\sqrt{8/3}$, and so on. Furthermore, when the variation in mass with speed of the electron is considered, its kinetic energy is no longer $\frac{1}{2} m_0 v^2$ but $m_0 c^2 \left(\frac{1}{\sqrt{1-\beta^2}} - 1 \right)$, where $\beta = v/c$, and c is the velocity of light; also the perinuclei

of the electron ellipses are no longer fixed, but show a slight forward progression. Taking these various factors into consideration, Sommerfeld has derived a somewhat complex expression for the energy of an atomic state, an expression which, however, on expanding and retaining the first two powers of the small quantity $\alpha^2 = (2\pi e^2/hc)^2$ (the square of the ratio-electron velocity in one quantum orbit of H atom: velocity of light), results in the more simple form for the frequency

$$\nu = (n, n') - (m, m') \text{ where } (n, n') = N \left(\frac{E}{e} \right)^2 \left[\frac{1}{(n+n')^2} + \frac{\alpha^2}{(n+n')^4} \left(\frac{E}{e} \right)^2 \left(\frac{1}{4} + \frac{n}{n'} \right) \right] \dots (3)$$

Here n, m are the angular quantum numbers, n', m' the radial quantum numbers, and the other symbols have their earlier significance. By virtue of the fraction n'/n there will be several frequencies, slightly differing from each other, corresponding to a given quantum sum $n+n'$; spectroscopically this means that the main lines specified by Bohr's simple theory will actually show a fine structure. The main structure of a line is determined by the quantum number of the orbit into which the electron falls. Thus the main structure of a Balmer line, where the electron falls into the 2 quantum orbit, is a doublet of separation, from (3), $(1, 1) - (2, 0) = N \left(\frac{E}{e} \right)^4 \frac{\alpha^2}{2^4}$, and since for H, $E = e$, this becomes $N \frac{\alpha^2}{2^4}$. This latter is an important constant in fine structure theory to which the symbol $\Delta\nu_H$, the separation of the H doublet, is applied. Similarly the main structure of a line in the 4686 series is a triplet of separation from (3) of

$$\left. \begin{aligned} (2, 1) - (3, 0) &= \left(\frac{E}{e} \right)^4 \cdot \frac{\alpha^2}{3^4} \cdot \frac{1}{2} = \frac{N\alpha^2}{3^4} \cdot \frac{2^4}{2} \cdot \left. \begin{aligned} (1, 2) - (2, 1) &= N \left(\frac{E}{e} \right)^4 \cdot \frac{\alpha^2}{3^4} \cdot \frac{3}{2} = \frac{N\alpha^2}{3^4} \cdot 2^4 \cdot \frac{3}{2} \end{aligned} \right\} \text{ for He+ atoms } E = 2e \end{aligned}$$

Now, furthermore, each of these main components is itself complex, the complexity arising from the quantum number of the orbit from which the electron has fallen. Thus each component of the $H\alpha$ doublet is a triplet, and each component of the 4686 triplet is itself quadruple, so that in all there are 12 components to 4686. In the case of ionized helium series, where the separations of components are magnified by 16, Sommerfeld's predictions have been completely verified by Paschen.⁵ In the case of the Balmer series a smaller separation, the large Doppler effect of the light atoms, and large Stark effects make the measurements and their theoretical interpretation difficult. Undoubtedly, however, the lines are doublets and the separation is of the right order.⁹

Confining attention to circle orbits, i.e. $n' = 0$, (3) becomes

$$\nu = N \left(\frac{E}{e} \right)^2 \left(\frac{1}{n^2} - \frac{1}{m^2} \right) \left[1 + \frac{\alpha^2}{4} \left(\frac{E}{e} \right)^2 \left(\frac{1}{n^2} + \frac{1}{m^2} \right) \right] \dots \dots \dots (4)$$

a formula which was first developed by Bohr.¹⁰ This formula shows clearly a second effect, in addition to the fine structure, of the introduction of relativity mechanics—namely, that the lines are all shifted slightly to the violet of the positions given by the simple formula (1). It is this formula which will be used to evaluate the Rydberg constant N_2 for helium. Curtis⁷ has also used (4) in determining the value of N_1 for hydrogen by including all his lines in a least-squares solution and solving for N_1 and α . This procedure is inadmissible since the formula refers only to circle components, whereas the measured wave lengths refer to the optical centres of gravity of the lines. To derive the position of the circle components from the measure of wave lengths, the value of α must be known. Here it has been assumed that $\Delta\nu_H = 0.36 \text{ cms}^{-1}$, a value taken from

Paschen's⁵ measurements of the structure of the enhanced helium lines and in fair agreement with the various measures⁹ of the separation of the hydrogen doublet. From this, taking $N = 1.097 \times 10^5$ $\alpha^2 = 5.25 \times 10^{-5}$. The procedure will then be to compute, by means of this value of α^2 , the positions of the circle components and from their frequencies, by the use of (4), the value of N_2 for helium.

The various steps of the process are given in Table 11. The first two columns contain the wave lengths in air of the enhanced helium lines selected for determining N_2 , and their probable errors, carried to three places of decimals. The component to $H\alpha$ at $\lambda 6560.04$ has been eliminated, because the wave length is an indication rather of the presence of the component than of its position (compare sec. 3). The component to $H\beta$ and the line at 4200 have also been eliminated because they are almost certainly blended with enhanced nitrogen lines (compare sec. 3). In the third column of the table the wave lengths in air are converted to their vacuum values by the Bureau of Standards Tables,¹¹ and these values in column four are turned into wave numbers by the formula $\nu = 10^8/\lambda$. These wave numbers refer, of course, to the optical centre of gravity of the various lines; the next step is to determine from these, by means of formula (3), the positions of the circle components. In order to do this, it is necessary, in addition to knowing the separation of the components, also to know their relative intensities. In view of our ignorance of electrical conditions in the stellar photospheres, the simple intensity relations suggested by Sommerfeld¹² have been used, namely:—in a doublet 2: 1, in a triplet 3: 2: 1, in a quadruplet 4: 3: 2: 1 and so on in the order of circle component and ellipse components where the intensity of the component decreases as the eccentricity of the orbit increases. This in effect states that circle orbits are most likely, and, the

TABLE 11—COMPUTATION OF N_2

λ air (l.A.)	p.e.	λ vac.	ν	ν (\odot compon.)	N_2	p.e.	Wt.
4685.704	$\pm .010$	4687.011	21335.56	21335.21	109722.9	± 0.2	44
5411.617	.045	5413.117	18473.64	18473.42	109720.4	0.9	3
4541.674	.032	4542.943	22012.16	22011.94	109720.6	0.8	5
4338.802	.043	4340.018	23041.38	23041.16	109719.4	1.1	3
4100.270	.058	4101.423	24381.78	24381.56	109716.6	1.6	1

more eccentric the elliptical orbit, the less likely its corresponding frequency is to occur,—a very probable assumption. A diagrammatic representation of the components of 4686 with their correct relative separations (using $\Delta \nu_H = 0.36$) and intensities is given in fig. 6. Paschen's notation is used, where the Roman numerals refer to the main components, I being due to the circle orbit, and where the letters refer to the superposed structure of these components, a referring to the circle component. The main separations are from (3)

$$\text{IIa—Ia} = (2, 1) - (3, 0) = 16 \frac{N\alpha^2}{3^4} \cdot \frac{1}{2} = 8 \left(\frac{2}{3}\right)^4 \Delta \nu_H = 0.57 \text{ cms.}^{-1}$$

$$\text{IIIa—Ia} = (1, 2) - (3, 0) = 16 \frac{N\alpha^2}{3^4} \cdot 2 = 32 \left(\frac{2}{3}\right)^4 \Delta \nu_H = 2.28 \text{ cms.}^{-1}$$

$$\text{Ia—Ib} = (4, 0) - (3, 1) = 16 \frac{N\alpha^2}{4^4} \cdot \frac{1}{3} = \frac{16}{3} \left(\frac{2}{4}\right)^4 \Delta \nu_H = 0.12 \text{ cms.}^{-1} \text{ etc.}$$

It is desired to determine the distance in wave numbers of the component Ia, the circle component, from the optical centre of gravity of the line. It can readily be computed, and as reference to fig. 6 will show, that Centre of Gravity of 4686 = Position of circle component + 0.35. Hence if the wave number of the centre of gravity of 4685 is 21 335.56, the position of its circle component in wave numbers is $21\ 335.56 - 0.35 = 21\ 335.21$. Similarly it may be shown for the Pickering lines, considering only the main

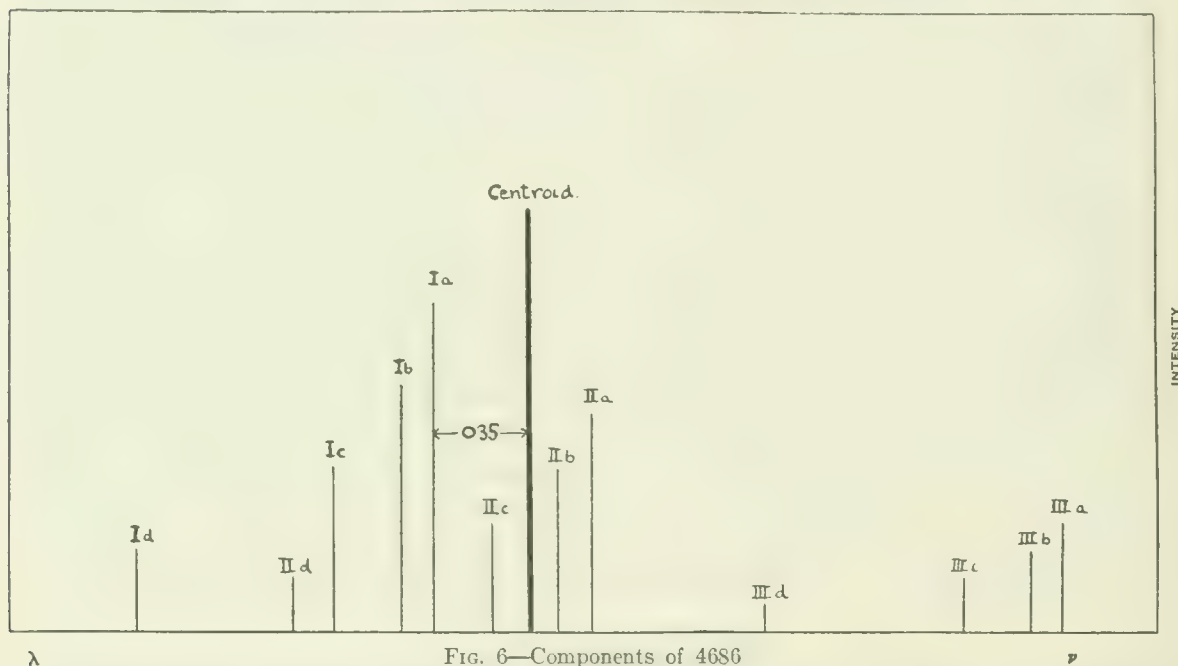


FIG. 6—Components of 4686

quartette structure and neglecting the superposed fine structure, which is greatly below the errors of measurement, that the positions of the circle components may be derived from the optical centres of gravity by subtracting 0.22. The positions of the circle components of the five enhanced helium lines as thus computed are given in the fifth column of Table 11.

The last step in the computation of N_2 is quite simple. For the ionized helium atom where $E = 2e$ and $\alpha^2 = 5.25 \times 10^{-5}$ equation (4) becomes

$$\nu = 4N_2 \left(\frac{1}{n^2} - \frac{1}{m^2} \right) \left[1 + 5.25 \times 10^{-5} \left(\frac{1}{n^2} + \frac{1}{m^2} \right) \right]$$

For any of the lines in Table 11, ν the position of the circle component, and n, m the quantum numbers of the final and commencement orbits respectively of the electron are known, and hence the value of N_2 may be computed. Thus for 4686, $n = 3$, $m = 4$ and $N_2 = 109\ 722.9$. It is interesting here to note that if, instead of using circle components and the relativistic equation (4), the original simple Bohr formula (1) of sec. 3 had been employed, the resultant value of N_2 for 4686 would have been 109 725.7, an error of nearly 3 in the units place. In a similar way the relativistic formula was used for the remaining four enhanced helium lines; the resultant values of N_2 are given in the sixth column and their probable errors, carried through from the original probable errors of the lines, are given in the following column.

In view of the character of the lines from which the wave lengths have been determined, it is evident that the five values of N_2 given in Table 11 are not of equal weight. The best and least arbitrary method of weighting these values would be inversely as the squares of their *true* probable errors. The true probable error, r , of any quantity is given by $r^2 = r_1^2 + r_2^2$ where r_1 is the accidental probable error and r_2 the systematic probable error. As pointed out in sec. 2 every care was taken to avoid systematic errors in the wave lengths; there is, however, one irremovable cause of systematic error, namely the possibility that the enhanced helium lines are blended with unsuspected lines of unknown origin. The magnitude of the possible systematic error introduced in this way will clearly vary with the character of the line. Thus the maximum error to which 4686 is open is less than 0.2 Å, since a line farther out than 0.5 Å would be readily detected so sharp is 4686; on the other hand a fuzzy line like 4541 might have a systematic error as great as 0.5 Å. It has, therefore, been assumed that the systematic probable error of a wave length is equal to its accidental error as given in the second column of Table 11; this in effect uses the accidental probable error as a measure of the character of the line, of which the probable systematic error in turn is a function. Now lines that have been measured in two stars are likely to have a smaller systematic error than those measured in one star, since, if the unsuspected line of unknown origin occurs in one star, it is not probable that it will occur with the same intensity, if at all, in a second star of different type. In calculating the "true" probable errors then the following formula has been used

$$r^2 = r_1^2 + \frac{r_2^2}{n} = r_1^2 \left(1 + \frac{1}{n}\right)$$

since r_2 is assumed equal r_1 . For lines, like 4686, measured in one star, $n = 1$; for lines like 4542 measured both in 10 Lacertæ and 9 Sagittæ, $n = 2$. The result of this is to give lines measured in two stars a lower relative "true" probable error than those measured in one star. Thus the ratio of errors of 4541: 4686 is, for accidental probable errors, 3.2 and for "true" probable errors, 2.8. The "true" probable errors of the wave lengths as thus computed are carried through, and the "true" probable errors of the values of N_2 are determined. The weights are then assigned inversely as the squares of these errors; these weights appear in the final column of Table 11. It might be thought that 4686 is thus assigned too high a weight, but in view of its sharp symmetrical character, in contradistinction to the fuzzy ill-defined lines of the Pickering series, it is evident that 4686 is of more value than the other four lines together. It may be noted that a more arbitrary method of weighting, earlier tried, led to closely the same weighted mean as that given by the weights finally adopted.

The resultant weighted mean of the five values of N_2 in Table 11 is

$$N_2 = 109\,722.3 \pm 0.44$$

This may be compared with Paschen's value of $N_2 = 109\,722.14 \pm .04$. These are in agreement within the probable error of the stellar value. They differ in the much greater probable error of the stellar value, scarcely a surprising result when the fuzziness of the stellar lines and the smaller linear dispersion are remembered.

SECTION 5—THE ELECTRON MASS AND RELATED PHYSICAL CONSTANTS

From the theory given in sec. 3, it will be recalled that the relations between the Rydberg constants for hydrogen and helium, and the various electronic and atomic constants are given by

$$N_1 = \frac{2\pi^2 m_0 e^4}{h^3 (1 + m_0/m_1)} \dots (5) \text{ for hydrogen where } m_1 = \text{mass of H nuclues.}$$

$$N_2 = \frac{2\pi^2 m_0 e^4}{h^3 (1 + m_0/m_2)} \dots (6) \text{ for helium where } m_2 = \text{mass of He nucleus.}$$

$$N_\infty = \frac{2\pi^2 m_0 e^4}{h^3} \dots (7) \text{ for an atom with nucleus of infinite mass.}$$

From these three equations may be derived immediately the result

$$N_1 (1 + m_0/m_1) = N_2 (1 + m_0/m_2) = N_\infty \dots (8)$$

from which, if the spectroscopic values of N_1 , N_2 and the mass ratio m_1/m_2 of the hydrogen and helium nuclei are known, the value of the electron mass may be determined. Paschen⁵ in his original work assumed m_1/m_2 to be the ratio of the atomic weights of hydrogen and helium, thereby neglecting the masses of the electrons. Flamm¹³, in a recomputation of Paschen's work, arranged (8) in a form to admit of the use of atomic weights in place of masses of the nuclei.

Flamm's method is used here and a brief summary may therefore be given. If M_1 , M_2 are the masses of a hydrogen and helium atom respectively, then the masses of the nuclei are $m_1 = M_1 - m_0$; $m_2 = M_2 - 2m_0$ since there is 1 electron in the normal hydrogen atom and 2 electrons in the normal helium atom. If these values of m_1 and m_2 be placed in (8) a quadratic equation in $1/m_0$ results. Solving for $1/m_0$ the expression under the radical is

$$\left(\frac{M_1 - M_2}{2}\right)^2 - M_1^2 \frac{N_1}{N_2} \left(1 - \frac{N_1}{N_2}\right) \dots$$

which may be expanded by the binomial theory to one or two powers of the very small quantity $1 - \frac{N_1}{N_2}$ (=approx. 0.000405). Furthermore, if L is the number of atoms in a gram atom, then $LM_1 = A_1$ where A_1 is the chemical atomic weight in grams of hydrogen. We have $M_1 = A_1/L$, $M_2 = A_2/L$, with the final resulting expression

$$\frac{1}{Lm_0} = \frac{A_2 - A_1}{A_1 A_2} \cdot \frac{N_1}{N_2 - N_1} + \frac{1}{A_2} \left[1 - \frac{A_1}{A_2 - A_1} \cdot \frac{N_1}{N_2} - \left(\frac{A_1}{A_2 - A_1}\right)^2 \left(\frac{N_1}{N_2}\right)^2 \left(1 - \frac{N_1}{N_2}\right) \right] \dots (9)$$

Similarly it may be shown that

$$N_\infty = N_2 + \frac{A_1 (N_2 - N_1)}{A_2 - 2A_1} \left[1 - \frac{A_1}{A_2 - A_1} \cdot \frac{N_1}{N_2} - \left(\frac{A_1}{A_2 - A_1}\right)^2 \left(\frac{N_1}{N_2}\right)^2 \left(1 - \frac{N_1}{N_2}\right) \right] \dots (10)$$

The expressions have been cast in this particular form, to avoid the production of large probable errors in determining the unknowns from quantities already subject to some uncertainty. They differ slightly in form, though they lead to the same results, from the expressions finally given by Flamm. The reason for this difference is another mode of expansion of the radical, and a further series of approximations introduced by Flamm.

In order now to determine the values of N_∞ and $1/m_0$, the values of N_1 , N_2 , A_1 , A_2 are required. By far the best determination of N_1 , the Rydberg constant for hydrogen, is that which has resulted from Birge's¹⁴ recomputation, using the method of sec. 4 with

probably more accurate intensity relations, of the measures by Curtis⁷ and Paschen⁵ of the Balmer lines. The resulting value is $N_1 = 109\,677.7 \pm 0.2$. The stellar value of N_2 as determined in the previous section is $N_2 = 109\,722.3 \pm 0.44$. Flamm¹³, in carrying through his calculations used, of course, Paschen's⁵ value of N_1 and N_2 . For the atomic weights of hydrogen and helium Flamm used the following:— $A_1 = 1.0007 \pm 0.00013$ (Morley and Noyes), $A_2 = 4.002 \pm 0.0017$ (W. Heuse). Since that time (1917), there have been redeterminations of the atomic weight of hydrogen by T. S. Taylor¹⁵, Burt and Edgar¹⁶, and of helium by Taylor. Taylor's values have been recomputed by P. A. Guye¹⁷. The whole matter has been considered by the International Committee¹⁸ who adopt the values 1.0078 for hydrogen and 4.000 for helium. The probable errors of these weighted means may be readily determined, and are found to be $A_1 = 1.0078 \pm 0.00003$; $A_2 = 4.000 \pm 0.0007$. Summarizing, in computing the stellar values of the universal constants the following have been used,—

$$\begin{array}{ll} N_1 = 109\,677.7 \pm 0.2 \text{ (Birge)} & : \quad N_2 = 109\,722.3 \pm 0.44 \text{ (stellar)} \\ A_1 = 1.0078 \pm 0.00003 & : \quad A_2 = 4.000 \pm 0.0007 \end{array}$$

With these values, carrying through the probable errors, the following immediately result from equations (10) and (9)

$$N_\infty = 109\,737.3 \pm 0.47$$

And $1/Lm_\odot = 1826 \pm 20$. Since $A_1 = LM$, it follows that $M_1/m_\odot = A_1/Lm_\odot$ and we have

$$M_1/m_\odot = 1840 \pm 20$$

Further since the electrochemical equivalent of silver¹⁹ is 0.00111827 gms./coulombs it follows that for the hydrogen atom $e/M_1 = 9647.0/1.0078$ in e.m. units. Therefore the ratio charge to the mass of the electron is given by $\frac{M_1}{m_\odot} \times \frac{e}{M_1}$, namely

$$e/m_\odot = (1.762 \pm 0.019) \times 10^7 \text{ e.m.u.}$$

To make any further progress the value of the charge carried by the electron must be known. In his original work Paschen⁵ derived the value of e from his value of $\Delta\nu_H = N\alpha^2/2^4$, where $\alpha = 2\pi e^2/hc$. The value of $\Delta\nu_H$, though very accurately determined by Paschen, has a large percentage error which results in an absurdly large probable error for the electron charge. In his revision of Paschen's work, Flamm, therefore, used Millikan's²⁰ very accurate value of the electron charge, $e = (4.774 \pm 0.005) \times 10^{-10}$ e.s.u. This procedure has also been adopted here, and results immediately in the values of a number of other constants. Thus from the value of e/m_\odot above, $m_\odot = (9.04 \pm 0.10) \times 10^{-28}$ gms. Assuming that the charge on the electron is spread uniformly over the surface and that the mass is entirely electromagnetic, the relation²¹ between the radius, charge and mass of the electron is given by $m_\odot = 2e^2/3ac^2$ where c is the velocity of light. This gives $a = (1.869 \pm 0.021) \times 10^{-13}$ cms. More important than these constants, however, is the fact that the value of Planck's radiation constant, h , may be computed if e is known. From (7) it follows that

$$h = e \sqrt{\frac{3/2\pi^2 m_\odot c}{N_\infty \cdot c}} \text{ where } c = 2.9986 \times 10^{10} \text{ cms. per sec. is the velocity of light.}$$

Inserting the necessary values there results

$$h = (6.567 \pm 0.042) \times 10^{-27} \text{ ergs. secs.}$$

Finally the constant c_2 , in the Planck radiation law, is related to h in the following manner,

$c_2 = ch/k$ where c is the velocity of light and k^{22} is the Boltzmann gas constant for one molecule, $k = (1.372 \pm 0.0014) \times 10^{-16}$ ergs/degrees. Substituting the necessary values

$$c_2 = 1.4353 \pm 0.0093 \text{ cms. degrees}$$

Flamm's revision of Paschen's work has been repeated, using equations (9) and (10), Birge's value of N_1 in place of Paschen's and the more recent values of the atomic weights. Paschen's values, thus revised, of these various universal constants are compared in Table 12 with what may be called the stellar values, derived immediately above. The first column of the table contains the symbol for the constant, the second the stellar spectroscopic value, the third Paschen's spectroscopic value and in the fourth column are given results from other methods. It will be noted that the stellar values are not only in good

TABLE 12—SPECTROSCOPIC UNIVERSAL CONSTANTS

Constant	Stellar Value	Paschen Value	Other Determinations
N_1	.....	.....	109 677.7 \pm 0.2—Birge ¹⁴ (Curtis and Paschen)
N_2	109 722.3 \pm .44	109 722.14 \pm .04	
N_∞	109 737.3 \pm .47	109 737.11 \pm .08	109 736.9 \pm 0.2—Birge ¹⁴
M_1/m_0	1840 \pm 20	1847.1 \pm 8.3	
e/m_0	1.762 \pm .019 $\times 10^7$	1.768 \pm .008 $\times 10^7$	β rays: 1.763 Bucherer ²³ , 1.769 Malassez ²⁴ . Zeeman Effect: 1.7636 Fortrat ²⁵ , 1.771 Gmelin ²⁶ . 4.774 \pm .005 $\times 10^{-10}$ Millikan ²⁰ .
e	.....	.....
m_0	9.04 \pm .10 $\times 10^{-28}$	9.01 \pm .04 $\times 10^{-28}$	
a	1.869 \pm .021 $\times 10^{-13}$	1.875 \pm .009 $\times 10^{-13}$	
h	6.567 \pm .042 $\times 10^{-27}$	6.547 \pm .019 $\times 10^{-27}$	6.5543—Birge ²² , mean of 7 independent determinations.
c_2	1.4353 \pm .0093	1.4309 \pm .0044	1.4320—W. W. Coblentz ²⁷

agreement with Paschen's spectroscopic values, which was to be expected since the two values of N_2 are identical within the errors of observation, but are also very accordant with determinations by other methods. It was not to be expected that there would be any startling changes, and these stellar values, weighted according to their unavoidably large probable errors, will serve, in addition to determinations by many other methods, to fix with certainty the values of these important universal constants. It is of interest, however, to note that these "stellar" determinations are in agreement with the terrestrial values, in so far as it shows that *the implicit assumption of identical atomic structure, identical electrons and identical laws of radiation on the earth and in the stars, is in some measure justified.*

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PART III—WAVE LENGTHS AND PHYSICAL CONDITIONS IN O-TYPE STARS

In Part II of this paper the O-type spectra were used to confirm Bohr's theory of spectral emission and to determine "stellar" values of atomic constants. In Part III, on the other hand, the O-type spectra are interpreted by physical theories so that some knowledge is acquired of the physical conditions in this class of stars and a possibly more rational classification of O-type stars thus becomes possible. In the first section are given the wave lengths of all the lines measured in the three O-type stars, with the estimated intensities of the lines and their probable origins. In the second section, from these observed spectra the temperatures and the relative abundance of hydrogen and helium in these stars are determined. The two methods (one of which is a slightly modified form of Saha's theory) which make this physical interpretation possible are fully explained and developed in the Appendix to the paper, entitled "Physical Interpretation of Stellar Spectra." Finally in the third section from the line intensities and from the probable stellar temperatures, a modification of the Harvard classification of O-type stars is suggested.

SECTION 6—WAVE LENGTHS IN O-TYPE STARS

Tables. In this section are given tables of the wave lengths, estimated intensities and identifications where possible of the lines in the three O-type stars, 10 Lacertæ, 9 Sagittæ and B.D. 35° 3930 N. Following the tables are some notes on the presence and absence of various elements together with a graphical comparison of the line intensities in the Harvard class B with the line intensities in the three O-type stars. The tables are arranged in the following manner. In the first column is given the stellar wave length (I.A.), a mean as a rule of at least four measures. No line is included unless it was measured on at least two plates; in this way chances of plate flaws appearing as lines are largely eliminated. In the second column of each table are given the probable errors of these mean wave lengths. A modification of Burns'† notation is used which has the advantage of indicating more fully the value of a given wave length than the probable error alone. The notation is,—

A indicates the mean of 6 or more measures and a probable error of the mean $0.00 - 0.01$.
 B indicates the mean of 4 or more measures and a probable error of the mean $0.01 - 0.04$.
 C indicates the mean of 4 or more measures and a probable error of the mean $0.05 - 0.10$.
 D indicates a probable error of $0.10 - 0.30$ or less than 4 measures.

In the third column is given the estimated intensity of the line on a scale of ten; each time a plate was measured the line intensities were estimated and the values in this column are means of these estimates. The probable origin of the line is given in the fourth column. Are lines are indicated by the symbol of the element, once enhanced lines by the symbol followed by a plus, thus C+ and doubly enhanced by the symbol followed by two plus signs, C++. Where the series relations of enhanced lines are not known the interpretation of these symbols is uncertain, and in the case of silicon and oxygen the

†References at the end of Part III.

notation of Lockyer and Fowler has been followed. It is to be noted that also in carbon and nitrogen the series relations of the lines are still unknown so that the symbols C+, C++ simply indicate spark and "super-spark" lines. The fifth column contains the laboratory wave length of the line in I.A. Wave lengths with an asterisk are those used as velocity standards (see Table 5, sec. 2). The final column of the table contains the name of the authority for the laboratory wave length. Complete references will be found at the end of Part III.

TABLE 13—WAVE LENGTH (I.A.) IN 10 LACERTAE

Stellar Wave Length (I.A.)	p.e.	Int.	Probable Origin	Laboratory Wave Length (I.A.)	Remarks
3933.55	B	4	Ca ⁺ —K	3933.664	Crew and McCauley ^{2 2}
3961.62	B	4	OIII	3961.60	Fowler ³
3964.73	A	4	He	3964.727*	Merrill ⁴
3968.32	B	4	Ca ⁺ —H	3968.465	Crew and McCauley ^{2 2}
3970.17	B	9	H —H _ε	3970.075	Curtis ⁵
4025.13	D	2	.....	.....	.....
4026.17	A	8	He	4026.189	Merrill ⁴ Blend He ⁺ 4025.63
4067.92	D	2	.....	.....	.....
4070.06	C	3	OII, blend	4069.635	69.903. Clark ⁶
4072.15	B	2	OII	4072.156*	Clark ⁶
4075.88	B	2	OII	4075.869*	Clark ⁶
4088.95	A	8	Si IV	4088.94	Lockyer ⁷ : 88.85 Lunt ⁸
4097.32	A	6	N ⁺	4097.327*	Fowler ⁹
4099.22	C	2	.....	.....	.....
4100.27	C	2	He ⁺	4100.05	Paschen ¹⁰
4101.72	A	9	H —H _δ	4101.738*	Curtis ⁵
4103.32	B	3	N ⁺	4103.393*	Fowler ⁹
4116.12	A	5	Si IV	4116.36	Lockyer ⁷ : 16.20 Lunt ⁸
4119.13	B	2	OII	4119.222*	Clark ⁶
4120.81	A	3	He	4120.812*	Merrill ⁴
4143.78	B	3	He	4143.759*	Merrill ⁴
4152.84	B	2	.....	.....	.....
4156.51	B	1	.....	.....	4156.5. Stellar line, Lockyer ⁷
4162.94	B	1	.....	.....	.....
4168.86	D	1	He?	4168.98	Runge and Paschen ¹¹
4186.93	A	2	.....	.....	.....
4189.79	D	1	OII	4189.793	Clark ⁶
4200.06	C	2	Blend He ⁺ , N ⁺	4199.86	He ⁺ Paschen ¹⁰ : N ⁺ 4200.06 Fowler ⁹
4212.33	B	2	.....	.....	.....
4253.94	D	2	S ⁺ ?	4253.61	Lockyer ⁷
4267.14	D	1	C ⁺	4267.14	Lockyer ⁷
4275.86	D	1	.....	.....	4276.0 Stellar line, Lockyer ⁷
4319.65	D	1	OII	4319.647*	Clark ⁶
4337.76	B	2	Ti ⁺ ?	4337.92	Lockyer ¹²
4338.87	C	2	He ⁺	4338.69	Paschen ¹⁰
4340.42	B	9	H —H _γ	4340.467*	Curtis ⁵
4349.37	B	2	OII	4349.435*	Clark ⁶
4366.74	D	1	OII	4366.906*	Clark ⁶
4379.21	B	2	N ⁺	4379.09	Fowler ⁹
4387.96	A	6	He	4387.928*	Merrill ⁴
4471.52	A	9	He	4471.477*	Merrill ⁴

Stellar Wave Length (I.A.)	p.e.	Int.	Probable Origin	Laboratory Wave Length (I.A.)	Remarks
4481.20	B	2	Mg ⁺	4481.195*	Fowler ² —Red comp. Int. 1, V. comp. Int. 2
4510.88	B	2	N ⁺	4510.91*	Fowler ⁹
4514.87	B	2	N ⁺	4514.865*	Fowler ⁹
4523.56	D	2	N ⁺	4523.59	Fowler ⁹
4534.82	D	2	N ⁺ blend	4534.57	35.07. Fowler ⁹
4541.62	B	3	He ⁺	4541.61	Paschen ¹⁰
4552.48	B	1	Si III	4552.47	Lockyer ⁷ ; 52.65 Lunt ⁸
4567.76	C	1	Si III	4567.72	Lockyer ⁷ ; 67.64 Lunt ⁸
4631.16	B	2	.....	.....	.....
4634.20	D	2	N ⁺	4634.165	Fowler ⁹
4640.54	D	1	N ⁺	4640.649	Fowler ⁹
4641.68	B	2	Blend OII, N ⁺	4641.827	Clark ⁶ ; 41.90 N ⁺ Fowler ⁹
4647.38	B	5	C ⁺⁺	4647.6	Merton ¹³
4649.06	B	1	OII	4649.148	Clark ⁶
4650.34	B	3	C ⁺⁺	4650.4	Merton ¹³
4651.59	A	3	C ⁺⁺	4651.6	Merton ¹³
4654.35	B	2	.....	.....	4654.4. Stellar line, Lockyer ⁷
4685.70	A	9	He ⁺	4685.74	Paschen ¹⁰ . 85.72 in star Frost ¹⁴
4713.18	B	5	He	4713.143*	Merrill ⁴
4859.08	C	5	Blend He ⁺ , N ⁺	4859.34	Paschen ¹⁰ ; 58.82 N ⁺ Fowler ⁹
4861.32	B	10	H —H β	4861.326*	Curtis ⁵
4921.78	C	5	He	4921.929*	Merrill ⁴
5015.70	B	4	He	5015.675*	Merrill ⁴
5411.62	C	4	He ⁺	5411.55	Paschen ¹⁰
5592.36	C	4	OIII	5592.35*	Fowler ³
5875.68	B	9	He	5875.618	Merrill ⁴
5889.86	C	4	Na	5889.963	Wood and Fortrat ¹⁵
5896.10	C	3	Na	5895.930	Wood and Fortrat ¹⁵
5919.19	D	1	.....	.....	.....
6278.33	D	3	.....	.....	.....
6558.25	C	4	.....	.....	.....
6560.04	D	3	He ⁺	6560.13	Paschen ¹⁰
6562.59	D	10	H —H α	6562.793*	Curtis ⁵
6678.39	B	4	He	6678.149*	Merrill ⁴

TABLE 14—WAVE LENGTHS (I.A.) IN 9 SAGITTAE

Stellar Wave Length (I.A.)	p.e.	Int.	Probable Origin	Laboratory Wave Length (I.A.)	Remarks
3933.60	D	5	Ca ⁺ —K	3933.664	Crew and McCauley ²²
3968.38	D	5	Ca ⁺ —H	3968.465	Crew and McCauley ²²
4088.89	C	6	Si iv	4088.94	Lockyer ⁷ : 88.85 Lunt ⁸
4097.24	B	7	N ⁺	4097.327*	Fowler ⁹
4100.83	D	4	He ⁺	4100.05	Paschen ¹⁰
4102.05	D	8	H —H δ	4101.738	Curtis ⁵
4103.53	D	5	N ⁺	4103.393	Fowler ⁹
4116.04	D	2	Si iv	4116.36	Lockyer ⁷ : 16.20 Lunt ⁸
4200.08	C	4	BlendHe ⁺ , N ⁺	4199.86	Paschen ¹⁰ : 4200.06 N ⁺ Fowler ⁹
4338.71	C	4	He ⁺	4338.69	Paschen ¹⁰
4340.45	B	9	H —H γ	4340.467*	Curtis ⁵
4379.25	D	3	N ⁺	4379.09	Fowler ⁹
4388.01	B	3	He	4387.928*	Merrill ⁴
4471.44	B	10	He	4471.477*	Merrill ⁴
4510.98	C	3	N ⁺	4510.91*	Fowler ⁹
4514.98	C	3	N ⁺	4514.865*	Fowler ⁹
4523.63	D	2	N ⁺	4523.59	Fowler ⁹
4534.48	D	2	N ⁺ blend	4534.57	35.07. Fowler ⁹
4541.76	C	6	He ⁺	4541.61	Paschen ¹⁰
4634.25	D	4E	N ⁺	4634.165*	Fowler ⁹
4640.60	D	5E	N ⁺	4640.649*	Fowler ⁹
4647.60	D	3	C ⁺⁺	4647.6	Merton ¹³
4650.72	D	3	C ⁺⁺ blend	4650.4	4651.6, Merton ¹³
4713.30	C	5	He	4713.143*	Merrill ⁴
4858.49	D	4	N ⁺	4858.82	Fowler ⁹
4860.74	D	9	BlendH, He ⁺	4861.326	H β Curtis ⁵ ; 4859.34 He ⁺ Paschen ¹⁰

TABLE 15—WAVE LENGTHS (I.A.) IN B.D. 35° 3930 N

Stellar Wave Length (I.A.)	p.e.	Int.	Probable Origin	Laboratory Wave Length (I.A.)	Remarks
3933.6	D	5	Ca ⁺ - K	3933.664	Crew and McCauley ²²
3965.3	D	3			
3968.4	D	4	Ca ⁺ - H	3968.465	Crew and McCauley ²²
3969.8	D	2	H - He	3970.075	Curtis ⁵
4025.7	D	2	He ⁺	4025.63	Paschen ¹⁰ . Computed from his N ₂
4085.2	D	2			
4091.6	D	1			Measured also as 4090.3, 92.9
4096.8	D	2	N?	4097.327	Fowler ⁹
4100.2	D	6	He ⁺	4100.05	Paschen ¹⁰
4101.8	D	9	H - H δ	4101.738*	Curtis ⁵
4199.8	D	6	He ⁺	4199.86	Paschen ¹⁰
4212.1	D	3			
4338.5	D	6	He ⁺	4338.69	Paschen ¹⁰
4340.5	D	9	H - H γ	4340.467*	Curtis ⁵
4391.6	D	2			
4470.9	D	0	He?	4471.477	Merrill ⁴
4541.2	D	7	He ⁺	4541.61	Paschen ¹⁰
4603.8	D	3			
4634.0	D	3E	N ⁺	4634.165*	Fowler ⁹
4640.4	D	4E	N ⁺	4640.649*	Fowler ⁹
4687.0	D	80E	He ⁺	4685.74	Paschen ¹⁰ . Line about 10A wide
4858.1	D	4	N?	4858.82	Fowler
4861.0	D	9	Blend H, He ⁺	4861.326	H β Curtis ⁵ ; 4859.34 He ⁺ Paschen ¹⁰
4390		3			Two measures differed by 4 A.

Comments on Wave Lengths. The following comments on the relative intensities of the lines and other interesting features in the wave lengths are arranged under different elements, the elements themselves being in order of increasing atomic number.

Hydrogen. In the three stars the Balmer lines are the most intense of any. Saha¹⁶ has predicted their disappearance before the disappearance of Mg + 4481 and ordinary He lines. Their continued presence in 9 Sagittæ and B.D. 35° 3930 N shows this prediction is not verified.

Helium. In 10 Lacertæ the strongest lines are those of the δ series of doublets, and the next most conspicuous series is the D series of singlets. In 9 Sagittæ the only lines showing are, in order of intensity 4471 ($1\pi - 3\delta$), 4713 ($1\pi - 3\sigma$), 4388 ($1P - 4D$). In B.D. 35° 3930 N, 4471 is just on the point of disappearing and no other He lines appear. From the work of Merton and Nicholson¹⁷ it appears that the enhancement of 4922, 4388, the later members of the D series of singlets, relative to 6678, indicates a comparatively low mode of excitation in 10 Lacertæ. The conditions in this star are apparently not unfavourable, judging from Merton and Nicholson's experiments for the appearance of the band spectrum of He¹³, which is apparently due to the transitory existence of the He₂ molecule. None of the unknown lines, however, in the star spectrum coincide with conspicuous lines in the band spectrum.

The spectrum of He + in the three stars has been discussed at length in sec. 3. It is of interest here merely to draw attention to the way the Pickering lines increase in intensity relative to the Balmer lines from 10 Lacertæ to B.D. 35° 3930 N. The behaviour of 4686 appears to be anomalous. Its disappearance in 9 Sagittæ may be due to the fact that it is just on the point of appearing as an emission line.

Carbon. In 10 Lacertæ there is a trace of 4267 which Fowler¹⁹ assigns to the once ionized atom. The triplet at 4647 found by Merton¹³ consists of three very sharp lines in 10 Lacertæ and the stellar wave lengths are probably accurate within ± 0.02 Å. Fowler¹⁹ has suggested that these lines are due possibly to C +. In 9 Sagittæ this triplet just shows but in B.D. 35° 3930 N it has disappeared entirely.

Nitrogen. The enhanced lines of this element, recently discussed by Fowler⁹, are conspicuous in 10 Lacertæ and are relatively stronger again in 9 Sagittæ. In B.D. 35° 3930 N they have practically disappeared save possibly for 4097 and traces of emission at 4634, 4640.

Oxygen. In 10 Lacertæ quite a number of the stronger OII lines appear. Also Fowler's³ OIII lines 5592, 3962 are very strong in 10 Lacertæ but have completely disappeared in 9 Sagittæ and B.D. 35° 3930 N.

Sodium. The D lines appear in 10 Lacertæ. Their appearance in a star of this temperature is anomalous and they are probably related to the sharp Ca + lines²³.

Magnesium. The enhanced line 4481², forming the first line of the fundamental series with a constant 4N, is present only in 10 Lacertæ and there it has been measured in less than half of the possible plates.

Silicon. In 10 Lacertæ Lockyer's Si III lines 4552, 4568 are just on the point of disappearing. Fowler¹⁹ provisionally assigns them to a twice ionized silicon atom Si ++. In both 10 Lacertæ and 9 Sagittæ the Si IV pair 4089, 4116, which Fowler¹⁹ suggests is due to Si + + +, is very conspicuous but has disappeared in B.D. 35° 3930 N.

Sulphur. This element is possibly represented in 10 Lacertæ by Lockyer's⁷ enhanced line 4253.61.

Calcium. The two sharp lines H and K appear in all three stars. In 10 Lacertæ and 9 Sagittæ they are definitely displaced to the violet, possibly also in B.D. 35° 3930 N. On any theory of ionization it is improbable that these lines would appear even in 10 Lacertæ let alone the other two stars. Work on early type spectroscopic binaries²¹ suggests that these lines and the D lines of sodium have their origin in a cloud either immediately surrounding the star or between the earth and the star.

Titanium. In 10 Lacertæ the line 4337.76 is possibly due to enhanced titanium.

Unknown Origin. All the lines in 9 Sagittæ have been identified but in 10 Lacertæ and B.D. 35° 3930 N there are a number of lines for which no identification has been found. Of the 75 lines in 10 Lacertæ there are 13 of unknown origin: three of these, viz., 4156.5, 4276.0, 4654.4 Lockyer⁷ notes as occurring in B-type stars. Of the 24 lines in B.D. 35° 3930 N there are 7 to which no identification can be assigned. Though these lines are all faint they have been measured on two or more plates and there is no reason to doubt their presence.

An inspection of the preceding comments makes it evident that the three O-type stars form, as regards line intensities, a continuous sequence. This is shown by the gradual decrease in intensity and final disappearance of the ordinary helium lines, the increase in intensity of the Pickering lines, the gradual disappearance of the Si iv and C ++ lines and so on in passing from 10 Lacertæ to B.D. 35° 3930 N. In this sequence 10 Lacertæ

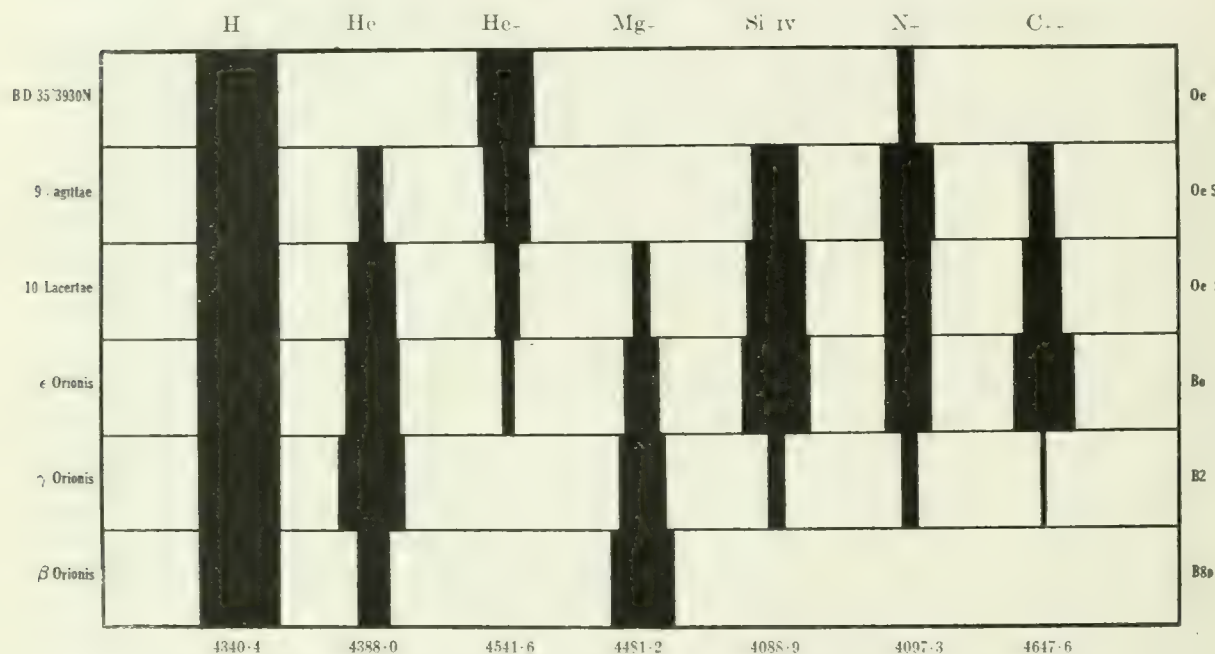


FIG. 7.—Intensities of Absorption Lines in B and O-Type Stars.

itself is closely related to the typical Bo star while 9 Sagittæ and B.D. 35° 3930 N are of "earlier" type. The general relations in line intensities are best shown by the type of diagram made familiar by Lockyer and his associates. In fig. 7 the intensities of a number of lines are shown graphically for the stars β Orionis (B8p), γ Orionis (B2), ϵ Orionis (Bo), the intensities of the lines in which are taken from Lockyer's tables⁷, and for 10 Lacertæ, 9 Sagittæ and B.D. 35° 3930 N, the line intensities being taken from Tables 13, 14, 15. The breadth of the lines indicates the intensity. From this diagram, which summarizes the preceding information, it is clear that the three O-type stars form, as regards line intensities, a unique and continuous sequence with the Harvard class B.

SECTION 7—PHYSICAL CONDITIONS IN O-TYPE STARS

Of the various physical problems which are raised by O-type spectra it is proposed in this section to consider only two—the probable stellar temperatures and the relative abundance of hydrogen and helium. The more difficult problem of these two and the more important, for on its solution rests the attack on the other, is that of determining the stellar temperatures. The faintness of the O-type stars makes difficult at present a direct determination of temperatures from the intensity distribution in the continuous spectra. The only other mode of attack, that of an application

of the methods developed in the Appendix to this paper on the "Physical Interpretation of Stellar Spectra," is contingent on a knowledge of the exact stage at which a line disappears, the series relations and ionization potentials of the element which gives rise to the line and the probable relative abundance of the element. While the paucity of lines and freedom from blends in these stars makes it possible to determine readily when a line has disappeared, the other two conditions are more difficult to fulfill in so far as, on the one hand, little or no laboratory work has yet been done on the characteristic O-type lines (enhanced silicon, carbon, oxygen and nitrogen) to ascertain their ionization potentials or series relations, and, on the other hand, the relative abundance of the element can only with more or less uncertainty be assumed identical with its abundance on the earth. As a result only the temperature of 9 Sagittæ has been determined directly from ionization theories; the temperature of the other two stars have been estimated from line intensity ratios. As for the other problem, the relative abundance of hydrogen and helium, its discussion arose from an attempt to obtain a physical interpretation of certain spectral peculiarities of O-type spectra noted in the previous section. These peculiarities were the persistence of the Balmer lines after the disappearance of enhanced magnesium and ordinary helium, contrary to Saha's prediction.¹⁶ The physical interpretation is comparatively simple when the stellar temperatures have once been estimated.

Stellar Temperatures. The two methods of determining stellar temperatures developed in the Appendix depend upon the application of the fundamental equation $b = Ka(1 - x)$. In this equation b is the number of atoms required to absorb all the radiation emitted per sq. cm. per sec. by the photosphere within ± 25 km. of a given wave length, and is therefore a function of the temperature. K is a constant (1.5×10^{20} for Saha's theory, 7.7×10^{20} for the electron collision hypothesis), a is the percentage abundance of the element and x is the fraction of once ionized atoms. The two methods developed in the Appendix, the one a slight modification of Saha's well known theory¹⁶ and the other based on the assumption that ionization is due entirely to free electron collisions, differ in the mode of calculating x for an element of known ionization potential at a given temperature, and also, as mentioned, in the value of the constant K . It should be noted that as K was determined from stellar data based on the generally accepted temperatures of 6000°K for the sun and $10,400^\circ \text{K}$ for BS stars, the temperatures given by an application of these ionization theories should be consistent with the lower temperatures in the Wilsing, Scheiner and Münch²³ scale. As both sides of the fundamental equation are functions of the temperature, the method of determining the temperature of the star from the disappearance of an arc or spark line, when the value of a , the relative abundance of the element, is known, is one of trial and error. The values of b and $Ka(1 - x)$ must be computed for several temperatures until that temperature is found for which the equation becomes an identity.

In 9 Sagittæ, as Table 14, Sec. 6, shows, the line $\text{Mg+ } 4481.19$ is not present. The value of b for this line for several temperatures may readily be computed and is the same for both theories. From the quantum relation $\Delta W = h\nu$ the amount of 4481 radiation absorbed by a single atom is 4.384×10^{-12} ergs. At $15,000^\circ \text{K}$ each sq. cm. of the

photosphere emits per sec. from Planck's law within ± 25 km of 4481.19 , 2.052×10^8 ergs. Therefore at $15,000^\circ \text{K}$, $b = (2.052 \times 10^8)/(4.384 \times 10^{-12}) = 4.681 \times 10^{19}$. In a similar manner the value of b may be computed for other temperatures. Now the disappearance of 4481 means that there are no more or at least only a small fraction of once ionized magnesium atoms left. From Saha's theory, as revised by Russell¹⁴, the fraction y of once ionized atoms for any given temperature may be readily computed as shown in the Appendix. Carrying through the necessary computations the following values result from Saha's theory on the assumption that $a = 1.426$, the same abundance in η Sagittæ that it has on the earth.

$$T = 15,000^\circ \text{K} : b = 4.681 \times 10^{19} ; Ka (1 - y) = 1.5 \times 10^{20} \times 1.426 (1 - 0.1410) = 1.837 \times 10^{20}.$$

$$T = 18,000^\circ \text{K} : b = 7.042 \times 10^{19} ; Ka (1 - y) = 1.5 \times 10^{20} \times 1.426 (1 - 0.6404) = 7.693 \times 10^{19}.$$

$$T = 20,000^\circ \text{K} : b = 8.782 \times 10^{19} ; Ka (1 - y) = 1.5 \times 10^{20} \times 1.426 (1 - 0.8587) = 3.023 \times 10^{19}.$$

Performing a graphical interpolation (see fig. 8) it is found that the fundamental equation becomes an identity at $T = 18,150^\circ \text{K}$. It will be noted that this is a much lower temperature than Saha¹⁶ himself assigns to the disappearance of $\text{Mg.} + 4481$, viz., $23,000^\circ \text{K}$. The chief reasons for this difference in estimates are Saha's neglect of the relative abundance of elements, and even more of the fact that as the temperature rises a greater number of atoms are required to absorb the increasingly intense 4481 radiation from the photosphere.

For the electron collision hypothesis, while the values of b remain as before, the quantity $Ka (1 - y)$ has to be recomputed in the manner shown in the Appendix. The results are, assuming as before that magnesium has the same abundance in η Sagittæ as on the earth

$$T = 15,000^\circ \text{K} : b = 4.681 \times 10^{19} ; Ka (1 - y) = 7.7 \times 10^{20} \times 1.426 (1 - 0.5576) = 4.858 \times 10^{20}.$$

$$T = 18,000^\circ \text{K} : b = 7.042 \times 10^{19} ; Ka (1 - y) = 7.7 \times 10^{20} \times 1.426 (1 - 0.8903) = 1.205 \times 10^{20}.$$

$$T = 20,000^\circ \text{K} : b = 8.782 \times 10^{19} ; Ka (1 - y) = 7.7 \times 10^{20} \times 1.426 (1 - 0.9531) = 5.154 \times 10^{19}.$$

From the graphical interpolation in fig. 8 it will be seen that on the electron collision hypothesis the temperature of η Sagittæ would be $18,925^\circ \text{K}$. The temperatures given by the two methods, which are based on different sets of assumptions, are accordingly in good agreement, and the value $T = 18,500^\circ \text{K}$ will here be adopted. It is to be noted, however, that this temperature, quite apart from the uncertainty as to the relative abundance of magnesium in the star, is subject to two possible errors. There is no trace of 4481 in η Sagittæ and in 10 Lacertæ it has been measured in less than half of the possible plates. It is therefore possible that the line has disappeared before the η Sagittæ stage is reached, in which case the temperature of this star would be higher than $18,500^\circ \text{K}$. On

the other hand the line 4481 is not absorbed by the normal once ionized magnesium atom, but only by one in which the atomic electron is in the 2δ orbit. Though a number of atoms owing to collisions with free electrons of appropriate velocity will be in this 2δ state, clearly not all of them will be, so that the temperature of $18,500^\circ\text{K}$. for the disappearance of $\text{Mg} + 4481$ will have to be revised downwards. As these two possible errors tend to balance each other, the temperature of $18,500^\circ\text{K}$ for 9 Sagittae is probably not greatly in error.

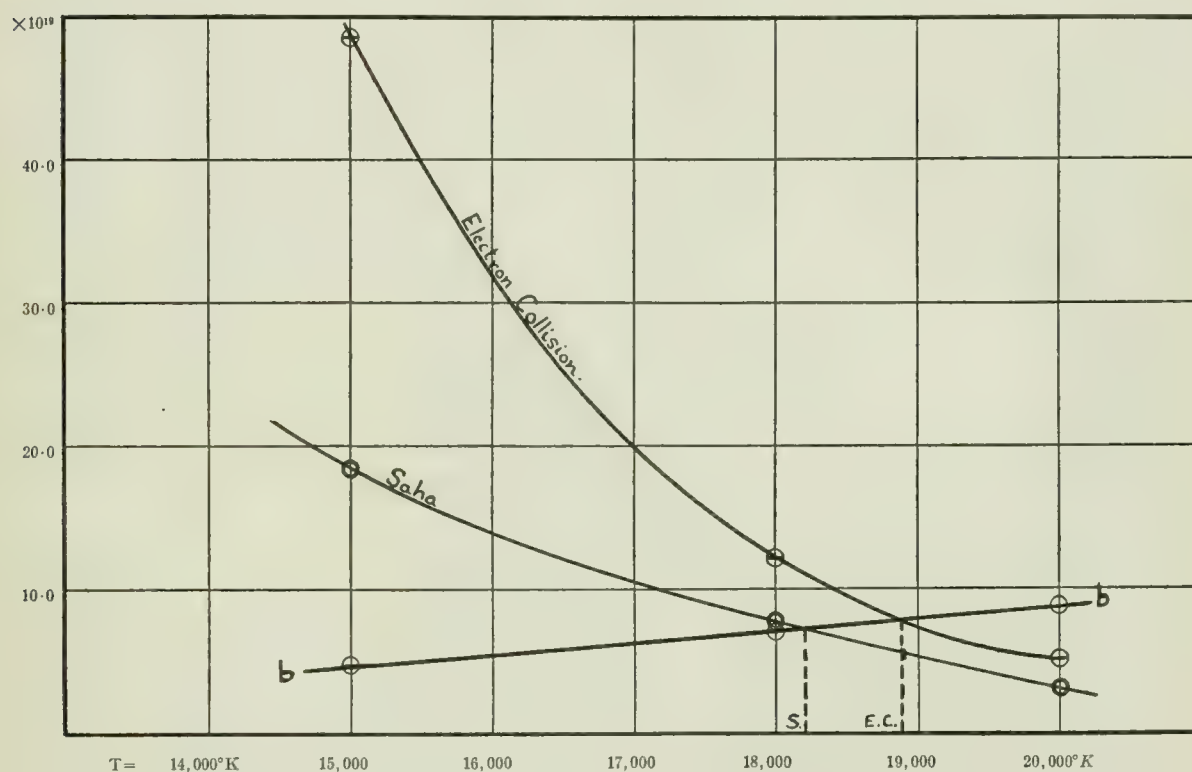


FIG 8—Temperature of 9 Sagittae from Disappearance of $\text{Mg} + 4481$

In *10 Lacertae*, since no lines disappear whose series relations or ionization potentials are known, the above ionization methods cannot be applied. However, since temperatures may be measured by any property of matter which varies continuously with temperature and since it has been shown that the intensity of lines in stellar spectra is a function of one main variable, the temperature²⁵, it appears probable that some estimate of the temperature of *10 Lacertae* may be arrived at from its line intensities. As noted in the previous section estimates of line intensities were made on all the plates and the means of these estimates are given in Tables 13, 14, 15, of Sec. 6 for the three O-type stars. Comparable with these estimates are those of Lockyer and his associates for the B-type stars.⁷ In the accompanying schedule are given the ratios of intensities of 4388 (He)/ $\text{H}\gamma$; 4541 (He_+)/ $\text{H}\gamma$; 4471 (He)/4541 (He_+); 4088 (Si IV)/4097 (N_+); and for 4647 (C_{++})/ $\text{H}\beta$ for

three B-type and three O-type stars. In the first column is given the star, in the second the Harvard type, in the third column the probable temperature, and the succeeding columns contain the line intensity ratios noted above. The temperatures of β Orionis (B8p) $10,000^{\circ}$ K and of ϵ Orionis (Bo) $13,000^{\circ}$ K are those given by Coblentz²⁶, as a result of his determination of intensity distribution in these stars in the spectral range 0.3μ to 10μ . The temperature of $12,000^{\circ}$ K adopted for γ Orionis is the mean of the temperatures given by Wilsing, Scheiner and Munch for γ Orionis, γ Pegasi and β Lyræ. The temperature of the other B2 star, ζ Cassiopeiæ, given by them was not included as being probably too low by reason of selective absorption of the Milky Way material in its neighbourhood. The temperature of $18,500^{\circ}$ K for 9 Sagittæ is of course that determined immediately above by means of the two theories of ionization. From the intensity ratios of the various pairs of lines given in this schedule it is now possible to interpolate graphically

Star	Harv.	Temperature	4388	4541	4471	4088	4647
	Type		H γ	H γ	4541	4097	H β
β Orionis.....	B8p	$10,000^{\circ}$ K	0.40	.....	.....	.....	.....
γ Orionis.....	B2	$12,000^{\circ}$ K	0.80	.....	.....	1.0	.....
ϵ Orionis.....	Bo	$13,000^{\circ}$ K	0.65	0.15	5.0	1.5	0.80
10 Lacertæ.....	Oe5	($15,000^{\circ}$ K)	0.67	0.33	3.0	1.3	0.50
9 Sagittæ.....	Oe5	$18,500^{\circ}$ K	0.33	0.67	1.7	0.9	0.33
B.D. 35°3930 N.....	Oe	($22,000^{\circ}$ K)	0.00	0.78	0.0	.....	0.00

and arrive at an estimate of the temperature of 10 Lacertæ. As a result it is found that the various pairs of lines give the following temperatures:— $4388/H\gamma = 12,800^{\circ}$ K $4541/H\gamma = 14,400^{\circ}$ K; $4471/4541 = 15,400^{\circ}$ K; $4088/4097 = 15,200^{\circ}$ K; $4647/H\beta = 16,600^{\circ}$ K with a mean in the round numbers of $15,000^{\circ}$ K. This temperature, in brackets in column 3 of the schedule, is assumed in what follows to be that of 10 Lacertæ.

In B.D. 35° 3930 N, as the above schedule shows, helium arc lines are just on the point of disappearing. An estimate of the relative abundance of helium on the earth may be obtained in the following manner. The emission of helium by volcanoes, from mineral springs and natural gases, its escape into and ultimate retention²⁷ by the earth's atmosphere, even if the temperature of the outer layers of this atmosphere has been as high as 300° C in the early history of the world,—all these things make it probable that the greater part of the element is in the atmosphere. F. W. Clarke²⁸ gives the ratio of helium to nitrogen (also chemically inert) in the atmosphere to be $0.0004/78.122$. As all the nitrogen is effectively in the atmosphere and its total percentage in the first ten metres of the earth's crust is 0.0383 , it follows that a lower limit to the percentage abundance of helium on the earth is 1.96×10^{-7} . If this be the abundance of helium in the stars then from Saha's theory the highest possible value of $K\alpha(1-x)$ will be $1.5 \times 10^{20} \times 1.96 \times 10^{-7} = 2.94 \times 10^{13}$ when $x = 0$. Since the individual atom absorbs from the quantum relation 4.394×10^{-12} ergs of 4471 radiation, it follows that the energy radiated per sq. cm. per sec. when the helium spectrum will appear will be 2.94×10^{13}

$\times 4.394 \times 10^{-12} = 1.29 \times 10^2$ ergs, corresponding to a temperature of 250° K. At this temperature, however, there would be no helium atoms with their electrons in the 1 p orbit necessary for 4471 to appear as absorption ¹⁶. Consequently if the abundance of helium be no greater than it probably is on the earth, the helium arc lines would never appear as absorption lines in stellar spectra. As, however, helium arc lines do appear it is evident that the relative abundance in the stars is different from the probable terrestrial abundance of helium. Consequently as no independent or probable value of a for helium can be obtained, it is impossible to use the two ionization theories to determine the temperature of B.D. 35° 3930 N from the disappearance of the helium arc lines in its spectrum.

For the present, until laboratory data on the series relations and ionization potentials of enhanced silicon, carbon and nitrogen are obtained, the temperature of B.D. 35° 3930 N can only be determined by extrapolation of the line intensity ratios. Using the values of these ratios given in the above schedule and including 10 Lacertæ at an estimated temperature of $15,000^\circ$ K, the following graphically extrapolated temperatures result for B.D. 35° 3930 N; $-4388/H\gamma = 21,600^\circ$ K; $4541/H\gamma = 19,700^\circ$ K; $4471/4541 = 25,800^\circ$ K; $4647/H\beta = 21,000^\circ$ K with a mean in round numbers of $T = 22,000^\circ$ K. This somewhat uncertain temperature, given in brackets in the above schedule, will be assumed in what follows to be the temperature of B.D. 35° 3930 N.

Summarizing, the following are the adopted temperatures for the three O-type stars:—

10 Lacertæ	— $15,000^\circ$ K Interpolated by line intensity ratios from ϵ Orionis and 9 Sagittæ.
9 Sagittæ	— $18,500^\circ$ K From the disappearance of Mg + 4481 on the two theories of ionization.
B.D. 35° 3930 N	— $22,000^\circ$ K Extrapolated from line intensity ratios in the three O-type stars.

of these temperatures that assigned to 9 Sagittæ is entitled to the greatest weight. The other two temperatures are effectively based on its determination and on the temperature of $13,000^\circ$ K given to ϵ Orionis by Coblentz²⁶.

Abundance of Hydrogen and Helium. The persistence of the Balmer lines in 9 Sagittæ and B.D. 35° 3930 N after the disappearance of enhanced magnesium and helium arc lines is, as previously noted, contrary to Saha's predictions on his original theory.¹⁶ However, it is shown in the Appendix that the disappearance of an arc or spark line is a function not only of the stellar temperature but also of the relative abundance of the element. It is, therefore possible, and is a matter of some interest, from the temperatures of the O-type stars derived immediately above, to compute by the use of the two ionization theories, what the relative abundance of hydrogen and helium must be to account for the apparently anomalous behaviour of their spectra.

Taking the ionization potential of *Hydrogen* as 13.545 volts, it may be shown from Saha's modified theory (see Appendix) what its relative abundance must be for its spectrum to disappear in 9 Sagittæ or B.D. 35° 3930 N. If $H\gamma$ disappeared in 9 Sagittæ at a temperature of $18,500^\circ$ K the relative abundance of hydrogen would be $a = 7.773$

$\times 10^{19} / [1.5 \times 10^{20} (1 - 0.8583)] = 3.66$. As the relative abundance of hydrogen on the earth (see Table 17, Appendix) is 15.459, it follows that if the stellar abundance of the element is comparable with its terrestrial value, the Balmer lines will persist after the temperature $18,500^\circ \text{K}$ is reached or after the disappearance of $\text{Mg} \lambda 4481$. In other words, when Saha's theory is modified to take account of the relative abundance of elements, the observed behaviour of hydrogen and enhanced magnesium is precisely what would be anticipated if the stellar abundances of the two elements are comparable with their terrestrial values. Similarly on Saha's theory if $\text{H}\gamma$ is to appear in B.D. $35^\circ 3930 \text{ N}$ at a temperature of $22,000^\circ \text{K}$ the relative abundance of hydrogen must be greater than $1.101 \times 10^{20} / [1.5 \times 10^{20} (1 - 0.9810)] = 38.63$; or the stellar abundance of hydrogen would have to be more than double its terrestrial value for the Balmer lines to appear in B.D. $35^\circ 3930 \text{ N}$. In fact it may readily be shown that if $a = 15.459$ for hydrogen in the stars, then the Balmer lines will disappear on Saha's theory at $21,000^\circ \text{K}$. These numerical results obtained from Saha's theory may be checked by the electron collision hypothesis. On this theory if $\text{H}\gamma$ disappears in 9 Sagittæ $a = 7.773 \times 10^{19} / [7.7 \times 10^{20} (1 - 0.9313)] = 1.47$; if $\text{H}\gamma$ disappears in B.D. $35^\circ 3930 \text{ N}$ $a = 1.101 \times 10^{20} / [7.7 \times 10^{20} (1 - 0.9800)] = 7.15$. If then the stellar and terrestrial values of the percentage abundance of hydrogen are comparable, on the electron collision hypothesis the Balmer lines will persist even in B. D. $35^\circ 3930 \text{ N}$, and it may be shown that $\text{H}\gamma$ will not disappear until a temperature of between $24,000^\circ \text{K}$ and $25,000^\circ \text{K}$ is reached. Summarizing, on Saha's theory the stellar abundance of hydrogen will have to be at least twice its abundance on the earth for the Balmer lines to be on the point of disappearing in B.D. $35^\circ 3930 \text{ N}$; on the electron collision hypothesis if the stellar abundance is less than half the terrestrial value the Balmer lines will still appear at $22,000^\circ \text{K}$. It may, therefore, be concluded with a fair degree of probability that the stellar relative abundance of hydrogen is of the same order as its abundance in the first ten miles of the earth's crust.

It has been shown in the discussion on the temperatures of B.D. $35^\circ 3930 \text{ N}$ that the relative terrestrial abundance of *Helium* is probably of the order of 1.96×10^{-7} . If the element is no more abundant than this in the stars, its spectrum will never appear. Once again it is of interest to compute (1) on Saha's theory and (2) on the electron collision hypothesis what the minimum values of the relative abundance of helium must be for $\lambda 4471$ to appear in 9 Sagittæ and B.D. $35^\circ 3930 \text{ N}$. Taking the ionization potential as 25.4 volts²¹, on Saha's theory for $\lambda 4471$ to appear in 9 Sagittæ at a temperature of $18,500^\circ \text{K}$, $a > 7.579 \times 10^{19} / [1.5 \times 10^{20} (1 - 0.0037)] = 0.507$; similarly for $\lambda 4471$ to be on the point of disappearing in B.D. $35^\circ 3930 \text{ N}$ at $22,000^\circ \text{K}$ $a = 1.064 \times 10^{20} / [1.5 \times 10^{20} (1 - 0.0663)] = 0.760$. On Saha's theory then the stellar abundance of helium lies between 0.507 and 0.760. It may be noted here that at $22,000^\circ \text{K}$ Saha obtains $x = 0.53$ in place of the value 0.0663 given above. The principal cause of this difference is that Saha used the resonance potential of 20.5 volts for helium in place of the ionization potential of 25.4 volts. Carrying through the computations on the electron collision hypothesis, it is found that for the disappearance of $\lambda 4471$ in 9 Sagittæ or in B.D. $35^\circ 3930 \text{ N}$, the stellar relative abundance of helium must lie between $7.579 \times 10^{19} / [7.7 \times 10^{20} (1 - 0.0101)] = 0.099$ and $1.064 \times 10^{20} / [7.7 \times 10^{20} (1 - 0.1078)] = 0.155$. Taking means from the

two theories the stellar relative abundance of helium must lie between 0.30 and 0.46, or it is probable that there is about two million times more helium in stellar atmospheres than there is in the first ten miles of the earth's crust.

From the observed spectra and the probable temperatures of O-type stars it has been concluded,—(1) that the stellar and terrestrial abundance of hydrogen are comparable, and (2) that helium is probably much more abundant in the stars than on the earth. These conclusions are scarcely surprising when the high temperatures and pressures that must exist towards the centre of an O-type star are recalled. Under these conditions it is to be expected that a certain small fraction of atomic collisions will result in nuclear disintegration, and the products of this disintegration will be helium and hydrogen nuclei³⁰. If then initially, say, there are 10^{11} hydrogen atoms and 10^3 helium atoms per cu. cm. (the ratio of hydrogen to helium on the earth approximately $10^8 : 1$), then after nuclear disintegration while the addition of 10^{11} hydrogen atoms per cu. cm. will not alter appreciably the relative abundance of that element, the addition of 10^{10} helium atoms per cu. cm. will increase the relative abundance of helium by 10,000 times of its terrestrial value. Further Rutherford's³⁰ working hypothesis suggests that at most there are not more than three hydrogen nuclei to a complex nucleus while there are, for example, as many as ten helium nuclei in the calcium nucleus. That is nuclear disintegration in the lower layers of the star will probably supply a greater number of helium atoms than of hydrogen atoms, and the final result will be a great increase in the relative abundance of helium over its initial value while the abundance of hydrogen will remain practically unchanged. This is precisely the result which is suggested by the observed O-type spectra. Accordingly nuclear disintegration in the lower layers of the star with subsequent diffusion of the products to the chromosphere is probably a satisfactory working hypothesis to account for the unchanged abundance of hydrogen and the great increase of helium.

SECTION 8—CLASSIFICATION OF ABSORPTION LINE O-TYPE STARS

One of the most important and informative modes of classifying stars is by their spectra. The Harvard system alone, of all the various classifications that have been proposed, is universally accepted and the reasons for its survival are not far to seek. For from the intensities of arc and spark lines more than 99 per cent of all the stars fall into one or another of the six great classes M, K, G, F, A, B: the remaining 1 per cent of the stars are divided among the minor classes N, R, O. Nor are these six main types unrelated, but are found to form, when expressed in the order M, K, G, F, A, B, a unique continuous sequence as regards the intensities of lines. From the investigations of Wilsing and Scheiner, Coblentz and others it has further become evident that this linear sequence is due to the fact that the spectral type is a function primarily of the temperature, a relation for which the theoretical investigations of Saha afford the soundest basis. The Harvard system is therefore, on account of its comprehensiveness, its facility and its firm, though unforeseen physical foundation, of fundamental importance in the classification of stars by their spectra.

Harvard subdivisions. In this final section of the paper, in the light of the data acquired in the previous sections, it is proposed to discuss the numerically insignificant

class O in an endeavour to bring its subdivisions more into harmony with the rest of the Harvard system. Within the Class O are comprised effectively all those stars, with the exception of those classified as B1, B0, which show the Pickering lines. The stars so classified may be divided into two main groups,—(1) absorption line stars showing occasional emission lines, and (2) stars showing nothing but broad emission bands. It is with the first of these groups only that this section is concerned, a group in which the present Harvard system recognizes three subdivisions:—

Oe5 Pickering lines and ordinary helium lines intense. 4089 > 4097. No emission.

Oe Pickering lines and ordinary helium as in *Oe5*. 4097 max. intensity. Emission 4638, 4686.

Od Pickering lines stronger, helium weaker. Emission 4638, 4686 stronger than in *Oe*.

In these subdivisions the practical distinction between *Oe5* on the one hand, and *Oe* and *Od* on the other, is afforded by the presence of emission at 4638, 4686. Now this procedure is inconsistent with the remainder of the Harvard classification, it is physically unsound, and it leads to the inclusion in the class *Oe5* of stars differing widely in the type as estimated by the absorption line intensities. The procedure is inconsistent in so far as the spectral class of later type stars from B to M which show emission lines is determined by the intensity of the absorption lines, the presence of bright lines being regarded merely as peculiarity (symbol *p*)—thus γ Cassiopeiæ Bop. In the Report of the Committee on Spectral Classification, adopted at the Rome meeting of the International Astronomical Union³¹, it was recommended that the presence of emission lines be denoted by the small letter *e*—thus γ Cassiopeiæ Boe; it is thus implicitly recognized in this Report that the presence or absence of emission lines does not determine type. Finally such a procedure leads to the inclusion of all O-type stars which show no bright lines in the class *Oe5*, irrespective of the strength of the absorption lines. The anticipated result is that the class *Oe5* has no physical significance and includes for example 10 Lacertæ and 9 Sagittæ, two stars whose temperatures differ some 3500° K.

The anomalous results brought about by this definition of the sub-class *Oe5* can best be seen when a greater number of stars are considered. In the course of his radial velocity programme of O-type stars, Dr. J. S. Plaskett has secured spectra of some thirty absorption line O's which he has kindly placed at the disposal of the writer for the purposes of this discussion. The B.D. numbers of these stars, their 1900 coordinates, their visual magnitudes and Harvard types (sent by Miss Cannon in advance of publication) are given in the first five columns of Table 16. In the succeeding three columns are given, from estimates with an eyepiece, the intensity ratios of the three pairs of lines 4471/4541, 4541 H γ , 4088 4097—intensity ratios which, as was shown in the previous section, change rapidly with the temperature and therefore rapidly with type. The two final columns contain the subdivision of the star as tentatively suggested in the next paragraph and remarks. An inspection of this table immediately shows that of 21 stars classified by Harvard as *Oe5*, from the intensity ratios 2 are more nearly B, 5 are similar to 10 Lacertæ, 4 lie between 10 Lacertæ and 9 Sagittæ, 3 are similar to 9 Sagittæ and 7 are earlier than 9 Sagittæ and approximating to B.D. 35° 3930 N. In other words, two-thirds of the stars placed in the class *Oe5* because they showed no trace of emission, are actually from the

TABLE 16—ABSORPTION LINE O-TYPE STARS

B.D.	R.A. 1900	Dec. 1900	Vis.	Harv.	4471	4541	4088	Prop.	Remarks
			Mag.	Type	4541	H γ	4097	Type	
°	h m	°							
40 501	2 16.7	41 02	7.5	Bo	2.8	0.25	0.53	O9	4686 absorption
58 467	2 19.5	58 25	8.04	Oe	0	0.6	—	O5e	4686 broad emission
56 693	2 35.5	56 28	8.4	Oe	0.7	0.6	—	O6e	4686 emission. One plate only.
52 726	3 48.0	52 22	6.70	Oe5	3.0	0.2	0.9	O9	4686 absorption
34 980	5 09.7	34 12	5.81	Oe5	4	0.2	1.5	O9	Almost identical 10 Lacertæ
37 1146	5 14.0	37 20	6.71	Oe5	0.8	0.6	—	O6	4686 faint absorption
9 879	5 29.6	9 52	3.66	Oe5	2	0.3	1.0	O8	λ_1 Orionis
			5.56	Oe5	∞	0	∞	B1	λ_2 Orionis
—5 1315	5 30.4	—5 27	5.36	Oe5	1.0	0.5	—	O6	θ Orionis C
					∞	0	—	B1	θ Orionis D.
—6 1241	5 30.5	—5 59	2.87	Oe5	3	0.2	2	O9	ι Orionis.
20 1284	6 03.7	20 31	7.40	Oe5	0.7	0.6	—	O6	
6 1303	6 31.1	6 10	7.3	B2	2	0.3	1.0	O8	Discovered by J.S.P.
6 1309	6 32.0	6 13	6.06	Bop	2	0.3	1.1	O8	Very massive star J.S.P., D.A.O.
10 1220	6 35.5	9 59	4.68	Oe5	1.1	0.45	0.8	O7	S Monoc.
—10 1892	7 04.6	—10 11	6.20	Oe5	0.7	0.4	—	O7	
—24 5176	7 14.5	—24 47	4.40	Oe5	5	0.15	1.4	O9—Bo	τ Can. Maj. Typical Oe5 star.
—24 13814	17 57.7	—24 22	5.86	Oe5	0	0.5	—	O5	9 Sagittarii
—24 13864	17 59.0	—24 24	6.79	Oe5	1	0.5	—	O6	
—18 4886	18 11.6	—18 30	6.37	Oe5	2	0.4	—	O8	
—20 5344	18 52.3	—20 33	6.73	Oe5	1	0.3	1	O8	
18 4276	19 47.9	18 25	6.29	Oe5	1.4	0.4	0.8	O7	9 Sagittæ. Eye-piece estimates.
35 3930N	19 59.8	35 45	7.2	Oe	0	0.6	—	O5e	Eye-piece estimates.
S			7.7		4	0.2	2	O9—Bo	
35 3949	20 01.9	35 19	7.4		0.9	0.5	—	O6	
35 3953	20 02.2	35 31	7.01	Op	5	0.2	2	O9—Bo	Broad emission 4686.
43 3571	20 17.1	43 32	6.83	Oa	0	0.6	—	O5e	Broad emission band at 4686.
44 3639	20 53.1	44 35	6.01	Oe5	0.8	0.5	0.6	O6	
43 3877	21 14.8	43 31	6.06	Oe5	1.7	0.3	—	O8	A Cygni. Broad weak lines.
56 2617	21 35.9	57 02	5.64	Oe5	0.6	0.5	—	O6	
61 2246	22 02.1	61 48	5.17	Oe5	8	0.2	1.3	O9—Bo	
58 2402	22 08.1	58 56	5.19	Od	1	0.5	—	O6e	λ Cephei. Diffuse lines.
38 4826	22 34.8	38 32	4.91	Oe5	2.7	0.2	1.4	O9	10 Lacertæ. Eye-piece estimates.

intensities of the absorption lines much earlier in type and approach more nearly the subtypes Od, Oe. Finally attention may be drawn to two other anomalies which have resulted from the use of the presence or absence of emission lines as a criterion of type. The one is the star B.D. 35° 3953 (R.A. 20^h 02^m.2.) classified by Harvard as Op because it shows a broad emission band at 4686. Actually from its absorption lines it is an Oe5 star but it cannot so be classified because it shows emission. The other case is the star B.D. 43° 3571 (R.A. 20^h 17^m.1) classified by Harvard as Oa because it shows a broad emission near 4686, a characteristic feature of this class. Actually, however, the star has absorption lines and from their intensity ratios the star is similar in type to B.D. 35° 3930 N.

Proposed Subdivisions. The preceding discussion has made it clear that the present subdivisions for the absorption line O-type stars are unsatisfactory. In tentatively suggesting any new mode of classifying it must be recalled, as was clearly shown in sec.

6 and 7 of this paper and as has long been more or less distinctly recognized, that the absorption line O-type stars form from the intensities of their lines and from their probable temperatures a unique and continuous sequence with the early B-type stars. It is, therefore, advisable in any proposed alterations of the subdivisions to use the decimal scale as in the major types B, A, F, G, K, M, where continuous sequences of line intensities also exist, and abandon the letter subdivisions of the present Harvard system; the more so as the Committee on Spectral Classification state that old symbols should not be used with new meanings.³¹ One other general condition that must be met by any satisfactory working classification of absorption line O's is, that a place be left for stars earlier in type than any in Table 16. Recalling that within the Harvard class O are comprised all those stars which show the Pickering lines, the class Oo might well be typified by a star in which these lines are on the point of disappearing. From Saha's theory, as modified in the Appendix for the relative abundance of elements, it is possible to compute at what temperature the Pickering series will disappear. It is found that taking the relative abundance of helium as 1.1 (probably a safe upper limit, see Sec. 7) the temperature at which the Pickering lines will be on the point of disappearing is about 29,000° K. If now B.D. 35° 3930 N ($T = 22,000^\circ \text{K}$) be taken as the typical star of the class O5, 9 Sagittæ ($T = 18,500^\circ \text{K}$) as the typical star of class O7 and 10 Lacertæ ($T = 15,000^\circ \text{K}$) of O9, the main framework of the tentative scheme is thus clearly outlined. A brief description of each one of the proposed types follows:—

Class Oo. Typical star—none known (Prob $T = 29,000^\circ \text{K}$). This class is characterized by the disappearance of the Pickering lines. The probable temperature is a very sensitive function of the relative abundance of the element helium.

Class O5. Typical star—B.D. 35° 3930 N (Prob. $T = 22,000^\circ \text{K}$). In this class the ordinary helium arc lines and the enhanced nitrogen lines have disappeared. In the typical star there is a trace of enhanced nitrogen emission at 4634, 4640 and also a very characteristic line of unknown origin at 4603.8. The intensity ratios for the class are $\frac{4471}{4541} = 0$; $\frac{4541}{\text{H}\gamma} = 0.6$.

Class O6. Typical star—B.D. 44° 3639 (Prob. $T = 20,000^\circ \text{K}$). In the typical star Si IV 4088.9 is weak and 4116.2 is absent or very faint. There is no trace of the enhanced carbon triplet at 4647. The intensity ratios which define the class are $\frac{4471}{4541} = 0.8$; $\frac{4541}{\text{H}\gamma} = 0.5$; $\frac{4088}{4097} = 0.6$.

Class O7. Typical star—9 Sagittæ (Prob. $T = 18,500^\circ \text{K}$). In the typical star enhanced nitrogen reaches its maximum strength. Ordinary helium is well marked and the enhanced carbon triplet is just beginning to appear. The enhanced magnesium line 4481 has disappeared, which serves to define the temperature. The intensity ratios are $\frac{4471}{4541} = 1.4$; $\frac{4541}{\text{H}\gamma} = 0.4$; $\frac{4088}{4097} = 0.8$.

Class O8. Typical star — λ_1 Orionis (Prob. $T = 17,000^\circ \text{K}$). This spectrum is characterized by the decreased strength of the enhanced nitrogen lines, the strengthening of ordinary helium and of the enhanced carbon triplet at 4647. In the typical star the fainter helium lines at 4713, 4388, 4143, 4120 are quite strong, and enhanced magnesium 4481 is barely present. The intensity rates are $\frac{4471}{4541} = 2.0$; $\frac{4541}{\text{H}\gamma} = 0.3$; $\frac{4088}{4097} = 1.0$.

Class O9. Typical star—10 Lacertæ (Prob. $T = 15,000^\circ \text{K}$). The typical star is characterized by the strength and sharpness of its lines. Si IV 4088, 4116 reach their maximum; Si III 4552, 4567 are on the point of appearing and Mg+ 4481 is clearly present. The enhanced nitrogen lines are present and the carbon triplet at 4647 is conspicuous. Fowler's O III lines at 3961, 5592 are strong. The intensity ratios are $\frac{4471}{4541} = 2.7$; $\frac{4541}{\text{H}\gamma} = 0.2$; $\frac{4088}{4097} = 1.4$.

Using these criteria it is now a simple matter, from eyepiece estimates of the intensity ratios of these three pairs of lines, to classify any absorption line O-type star. These tentative classes for some thirty-three O-type stars are given in the ninth column of Table 16. The suggestion embodied in the Stellar Classification Report ³¹ is here adopted, and the letter e following the type indicates the presence of an emission line or lines in the spectrum. That the proposed classification is on the whole more satisfactory than the present Harvard system is shown by the distribution of stars among the various subdivisions. Of the 33 stars in Table 16 Harvard classifies as B2-1; Bo-2; Oe5-21; Oe-3; Od-1; Op-1; Oa-1; and unclassified 3. On the face of the matter it seems unreasonable to suppose that the vast majority of the absorption line O's should fall into one subdivision of the classification. On the proposed classification of the 33 stars there is in the subclass B1-2; O9-9; O8-6; O7-3; O6-9; O5-4;—on the whole a much more uniform and probable distribution amongst the various temperatures.

In conclusion there is at least one criticism that may be urged against this tentative scheme—namely it contains no place for that group of O-type stars showing emission bands with no trace of absorption lines. Unfortunately knowledge of this group of stars is still so meagre as to make a discussion of their place in any scheme of classification difficult. Two things at least, however, are evident. First the pioneer investigation of W. W. Campbell ³² has made it clear that typical stars of this group B.D. 35° 4001 (Ob), B.D. 35° 4013 (Oa), and B.D. 37° 3821 (Ob), spectra of which secured here show no trace of absorption line, have bright bands coincident with ordinary helium at $\lambda 5876$, with Mg+ 4481 and with O III 5593. The presence of these lines at once makes it clear that these stars are not of higher temperature than the tentative type O7, and that as a group the emission band or Wolf Rayet stars are not of earlier type than the absorption line O's. In the second place Wright ³³ has shown in a number of typical cases that these emission band stars are most closely related to the planetary nebulae. Obviously the width of the emission lines and the weakness of the continuous spectrum suggest, that the radiation has had its origin in something quite different from a star with a well defined photosphere and a tenuous chromosphere. The observed spectra indicate if anything a veiled photosphere and a high pressure chromosphere. Notwithstanding these two facts it must, however, be remembered that the absorption line O's and the Wolf-Rayet stars quite frequently have in common more or less ill-defined emission bands in the neighbourhood of 4686, a fact which suggests some connection between the two groups. Until more is known of this interesting group of emission band stars, it may be assumed as a possible working hypothesis that the Wolf Rayet stars form a side chain with the O's thus A, B, O and A,B, Wolf Rayet, Planetary Nebulae? just as the spectral series divides into two branches at the other end, viz., G, K, M and G, K, R, N. The physical inter-

pretation of such an assumption would be that the exceptionally massive stars followed the Wolf Rayet branch until they were "blown out" by radiation pressure³¹ into planetary nebulae. In any case the assumption fits the facts about these stars as they are now known, and justifies to some extent the complete omission of the Wolf Rayet stars from the tentative scheme for the absorption line O's.

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APPENDIX PHYSICAL INTERPRETATION OF STELLAR SPECTRA

The purpose of this Appendix is to explain the methods which are used in Sec. 7, Part III, to determine the temperatures and the relative abundance of elements in O-type stars. This problem of the physical interpretation of stellar spectra is made complex by the fact that the star spectrum is a function probably of at least four independent variables—the chromospheric temperature and pressure, the relative abundance of elements and the free electron concentration. That any progress in the solution of the problem has been made at all is largely due to the pioneer work of M. N. Saha, who in a series of papers has laid down the guiding principles for a successful attack. In this Appendix two independent methods of determining temperature and relative abundance of elements from an observed stellar spectrum are outlined, the more important one of which is a slight extension of Saha's theory. The other method was devised primarily to act as a check on the numerical results which applications of his theory gave.

The appendix is divided into three sections. In the first of these a review is given of current and well established theories on the origin of spectra on which basis any physical theory of stellar spectra must rest. In the second section Saha's theory is outlined and modified to allow for the relative abundance of elements. It is shown that with this modified theory the "anomalous" behaviour of barium and sodium in the sun can be explained without any additional hypothesis. Finally in the third section certain possible imperfections in Saha's postulates are considered and an alternative hypothesis of ionization by electron collisions is developed.

SECTION A—THE ORIGIN OF SPECTRA

Bohr's^{1*} theory of the atom with one electron shows that there is associated with the appearance of a given line a definite amount of energy. In the normal atom where the sum of potential and kinetic energies is a minimum, the electron revolves in the 1 quantum orbit. In order to produce an emission line the electron must first be lifted out of that 1 quantum orbit, either to some more distant orbit, or to infinity. Thus the line 1216, the first line of Lyman's ultra violet hydrogen series, is emitted by a hydrogen atom in which the electron falls from the 2 to the 1 quantum orbit. In order, therefore, to bring the hydrogen atom into the necessary preliminary condition to radiation, the electron will have to be lifted from the normal 1 quantum to the 2 quantum orbit. Directly from Bohr's theory it is seen that this involves the expenditure of $Nh(1 - \frac{1}{2^2}) = 1.617 \times 10^{-11}$ ergs of energy per atom. In order for the hydrogen atom to emit any possible line of its spectrum it is necessary to lift the electron to infinity. Again from Bohr's theory this requires $Nh = 2.156 \times 10^{-11}$ ergs. Thus it will be noted that, for an atom with stationary orbits (like the Bohr model), the amount of energy required for the production of a given line is obtained from the quantum relation $\Delta W = h\nu$,—the frequency times Planck's constant.

*References will be found at the close of the Appendix

Now the work of Franck and Hertz², McLennan³ and others has shown that relations of precisely this form hold also for more complex atoms,—atoms with more than one electron. Their experimental procedure has been to bombard the monatomic atoms of some metallic vapour with free electrons emitted by an incandescent filament and accelerated by known potentials. Thus it has been shown that for sodium, when the free electrons have a potential drop of 2.09 volts, known as the resonance potential, a “single line spectrum” occurs,—the well known D lines. No further spectral lines appear until the electrons have a potential drop of 5.11 volts, known as the ionization potential, when suddenly the whole spectrum flashes out. Now the frequency of D_2 , λ 5889.963 is $\nu = 5.09 \times 10^{14}$. Hence from the quantum relation the energy to produce D_2 is $6.554 \times 10^{-27} \times 5.09 \times 10^{14} = 3.34 \times 10^{-12}$ ergs = 2.09 volts. Similarly the frequency of the limit of the π series of sodium is 1.24×10^{15} , and the energy necessary to produce this limit is again given by the quantum relation to be 8.15×10^{-12} ergs = 5.11 volts. The close similarity between the energy relations in the hydrogen and sodium spectrum is at once evident, and strongly suggests the existence in the sodium atom of stationary orbits. Relations similar to these have been found for the alkalis and alkaline earths⁴ in the first two columns of the periodic table.

These experiments have led to the formulation of the following theory by Sommerfeld⁵ for atoms with more than one electron. Fixing attention on one electron of an atom of atomic number n , the charge on the rest of the atom, or the “core,” is $+ne - (n-1)e = +e$. When the single electron is sufficiently far removed, the atomic core (1 nucleus, $n-1$ electrons) will act like a point charge $+e$. The single electron will then revolve in stationary orbits about this core, and various lines will be emitted as the electron drops from outer to inner orbits so that their frequencies will form series of the form $N \left(\frac{1}{n^2} - \frac{1}{m^2} \right)$. The innermost or normal orbit of the electron is that to which it falls in emitting the limit of the principal series. It is, therefore, designated by the symbol $1s$; other orbits are indicated by the terms of the usual series notation⁶. To a second approximation, considering the residual repulsive actions of the $n-1$ electrons in the atomic core, the potential energy of the single electron will be $-\frac{e^2}{r} \left(1 - \frac{c_1}{r^2} \right)$ where c_1 is a constant and r is the radius of the orbit. This leads to frequencies connected by the well known Rydberg relation $\nu = N \left[\frac{1}{(n + \mu_1)^2} - \frac{1}{(m + \mu_2)^2} \right]$, where N is the universal Rydberg constant. In this way a satisfactory theory is obtained of the spectral emission of more complex atoms, which are shown to behave in a manner closely similar to the one electron atom.

Two consequences of this complete Bohr-Sommerfeld atomic theory must be noted, An *emission line spectrum* is given when the electron falls from outer orbits inwards, the loss of energy of the atomic system appearing as monochromatic radiation whose frequency is given by the quantum relation. On the other hand, an *absorption line spectrum* is given when the electron is lifted from within outwards by the absorption of radiation, whose frequency, from the quantum relation, corresponds to the necessary increase in energy of the atomic system. The principal series of an element will appear as absorption lines for undisturbed atoms since the electrons are in the $1s$ orbit or normal orbit and the various lines are given by lifting the electron from this to outer orbits,—the $1p$, $2p$, $3p$,

..... In order, however, for the subordinate series to appear as absorption, it is necessary to disturb the atom in some manner so as to lift the electron to the 1p orbit when the sharp and diffuse series can appear, or to the 2d orbit, when the fundamental series can appear by the absorption of radiation. The classical example is sodium whose "cold" vapour shows 33 members of the principal series as absorption, but whose atoms must be electrically excited to show the subordinate series in absorption.

The second consequence of the Bohr-Sommerfeld atomic theory has to do with the ionization of atoms. When the atom permanently loses through ionization 1 electron, the charge on the atomic core becomes $ne - (n - 2)e = +2e$. As a result the series lines will have their Rydberg constant multiplied by 4 in precisely the same way as the series constant for the ionized helium atom is $4N$. If the atom permanently loses two electrons, the charge on the core will be $+3e$ and the series constant will be $9N$. Thus from the series relations in the line spectrum it will be possible to tell the state of ionization of the atom; once ionized atoms will give series with a constant $4N$ like the Pickering lines, twice ionized atoms will give series with a constant $9N$, possibly like $4647\text{ C}++$ and so on. Now Kossell and Sommerfeld⁷ have shown that it is possible to predict one other thing about the spectrum of an ionized atom. Clearly when an atom has lost one electron, in the number of remaining electrons it will resemble the atoms of the element immediately preceding it in the periodic table. Kossel and Sommerfeld, therefore, predict that the spectrum of the once ionized atom or the once enhanced spectrum of an element will resemble the arc spectrum of the element immediately preceding it in the periodic table. This relation, called the Displacement Law, they were able to verify substantially at the time of announcement, and it has since received important additional support.⁸

SECTION B—SAHA'S THEORY AND THE ABUNDANCE OF ELEMENTS

In a series of four papers Dr. M. N. Saha⁹ has recently brought forward a very remarkable and highly satisfactory theory of the solar and stellar spectra, which is based on the well established theories of atomic structure and spectral emission outlined above. The fundamental postulate of his theory is that the disappearance of the arc spectrum of an element in a star means that all the atoms are once ionized and that no neutral atoms are left, the disappearance of the first spark spectrum with constant $4N$ means that there are neither neutral nor once ionized atoms left and so on. In short the presence or absence of arc, spark and "super spark" spectra is an indicator of the degree of ionization of the atoms of that element. Saha treats this ionization or removal of one or more electrons as a reversible chemical reaction of the form, say for sodium, $\text{Na} = \text{Na}^+ + e - U$, where a sodium atom is reversibly dissociated into an ionized sodium atom and a free electron by a certain amount of energy U . From the law of mass action, if x be the fraction of neutral atoms so dissociated, it follows that $x^2 / (1 - x^2) = K/P$ where K is a function of the temperature alone and P is the total pressure. The exact form of K Saha deduces from thermodynamical considerations and from the Nernst heat theorem, so that the following expression results, where the numerical values of the various entropy constants and specific heats have been inserted,

$$\log \frac{x^2}{1 - x^2} \cdot P = - \frac{U}{4.571T} + 2.5 \log T - 6.5 \dots\dots\dots (1)$$

U, the heat of dissociation in calories per gram molecule, may be readily deduced from the ionization potential for a single atom. Thus the work required to dissociate 1 gram atom of sodium, whose ionization potential is 5.11 volts, is 1.176×10^5 calories. Accordingly from equation (1) knowing the temperature and total pressure in the medium, the fraction x of once ionized atoms of elements of known ionization potential may be readily calculated. Saha has performed such computations, and in his papers he gives tables for x for various elements at different temperatures and pressures. Assuming the pressure in stellar chromospheres to lie between an atmosphere and one-tenth of an atmosphere, from the disappearance of the Ca line 4227, the Balmer lines, the Mg+ line 4481 and so on, he is able to calculate stellar temperatures which are in good agreement with the values determined from spectrophotometric data.

In his physical theory of stellar spectra, as outlined above, Saha has not considered the question of the relative abundance of elements. This, it may, however, be readily shown is a factor of vital importance. Consider two elements of the same ionization potential, the one with n_1 atoms in the chromosphere, the other with n_2 , where $n_2 > n_1$. Let n be the number of neutral atoms required for the arc spectra to be just on the point of appearing; to a first approximation n will be the same for both elements. Then the arc spectrum of the less abundant element will disappear when $n_1 (1 - x_1) = n$ and of the more abundant when $n_2 (1 - x_2) = n$. The more abundant will, therefore, disappear at the higher temperature where the difference between the fractions of once ionized atoms for the two elements is $x_2 - x_1 = \frac{n}{n_1} \left(1 - \frac{n_1}{n_2}\right)$. If n , the minimum number of atoms for an arc spectrum to be on the point of appearing, is comparable with n_1 , then the difference between x_2 and x_1 will be directly dependent upon the relative abundance of the two elements and the more abundant element will act precisely as if it had a much higher ionization potential. If n , however, is small compared with n_1 , then the difference $x_2 - x_1$ is numerically small, but the more abundant element will still act as if it had the higher ionization potential, and the temperatures at which the two arc spectra disappear will differ by probably as much as before. For note that if n/n_1 is a very small fraction then x_1 differs but little from unity and x_2 even less. But as the form of equation (1) shows, x increases to the value unity with increase of temperature asymptotically, so that, provided the values of x are sufficiently near unity, no matter how small numerically the difference $x_2 - x_1$ may be, it will still correspond to large differences in temperature. It is, therefore, evident that whether the minimum number of atoms for the bare appearance of a spectrum is large or small compared with the total number available, neglect of the relative abundance of elements is likely to lead upon occasion to grave incongruities.

The complete treatment of relative abundance is as follows. A given line in a spectrum will be on the point of disappearing when the number of atoms which absorb it is a certain minimum. This minimum number is determined by the wave length of the line and the temperature of the photosphere. The amount of energy of this wave length absorbed by a single atom may be determined from the quantum relation $\Delta W = h\nu$, using the frequency of the line under consideration. Thus when sodium vapour is absorbing D_2 radiation, each atom absorbs 3.34×10^{-12} ergs. If now the photosphere is radiating per sq. cm. per sec. 10^5 ergs of D_2 radiation (temperature about 5000° K.), then

to completely absorb this radiant energy will require 3×10^{17} sodium atoms per sq. cm. column per sec. in the stellar chromosphere. If the photosphere is radiating 10^3 ergs per sq. cm. per sec. (corresponding to $15,000^\circ$ K), then 3×10^{19} sodium atoms per sq. cm. column per sec. are required for complete absorption. The number of atoms required for complete absorption is, therefore, a function of the temperature of the photosphere. For the line to be just on the point of appearing there must be a certain fraction of this number available. Wedge spectra secured here indicate that the ratio of intensity absorption line: continuous spectrum for the faintest lines is about 1 : 10. Then if 3×10^{17} sodium atoms give complete absorption, 9/10ths of that number will give a line which just barely appears.* Irrespective of the number required for complete absorption, some constant fraction k_1 of this number will give the number of atoms for which the line will barely appear. If b is the number of atoms for complete absorption (a number readily calculable from the wave length of the line and the temperature of the photosphere), then $k_1 b$ is the number of atoms for the line to be just appearing where k_1 is some constant fraction.

Now this number $k_1 b$ will be attained at different temperatures by elements of the same ionization potential depending upon their relative abundance. If a is the percentage abundance of the atoms of a given element and k_2 is the number of atoms per sq. cm. column for an element with percentage abundance unity, then $k_2 a$ is the number of atoms of the element per sq. cm. column. At the temperature where $k_1 b = k_2 a (1 - x)$ or where K is a constant when

$$b = Ka (1 - x) \dots\dots (2)$$

then, and only then, will the given line of the given element disappear. In this equation b can be computed from the temperature of the photosphere by Wien's or Planck's law in the form $E_\nu d\nu = \frac{2\pi h\nu^3}{c^2} e^{-h\nu/kT} d\nu$, where $d\nu$ has been taken uniformly throughout this paper to correspond to an increment of frequency of 50 kms. and k is the Boltzman gas constant. This gives the radiation in ergs per sq. cm. per sec. at a temperature T . The amount of energy of given wave length absorbed by a single atom is given by the quantum relation. Then the value of b is,--radiation of given wave length emitted per sq. cm. per sec. divided by energy of given wave length absorbed by a single atom. Of the value of a , the percentage abundance of different elements in the stellar chromospheres, nothing definite is known. In order, however, to arrive at some estimate of the relative

*An alternative and possibly a clearer mode of arriving at these results is as follows. The basic assumption is that when a line is just on the point of appearing or disappearing the ratio of intensity in the absorption line (I) to the intensity in the continuous spectrum (I_0) is a certain constant, viz $I/I_0 = j$. Now if the ordinary laws of absorption held (i.e. Lambert's law where the fraction of light absorbed is independent of the original intensity), then for a certain fixed number of atoms $I/I_0 = j$ would be true irrespective of the value of I_0 , that is, irrespective of the photospheric temperature. But this is not the case. Each atom can only absorb a finite quantum of radiation $\Delta W = h\nu$ ergs. Thus if n atoms are enough to make an absorption line just appear for photospheric intensity I_0 , then $I = I_0 - n \cdot \Delta W$ and $j = (I_0 - n \cdot \Delta W) / I_0$. If now I_0 is increased by some factor α owing to a rise in temperature of the photosphere, then n will have to be increased to n' where $(\alpha I_0 - n' \cdot \Delta W) / \alpha I_0 = j$ or $n' / n = \alpha$. In short the number of atoms necessary for a line to appear must increase in the same ratio as the photospheric radiation. Further if b is the number of atoms required for total absorption, then $b \cdot \Delta W = I_0$ and $I/I_0 = j$ becomes $(b - n) / b = j$ or $n = b (1 - j)$. That is, the number of atoms necessary for a line to be on the point of appearing is a function of the photospheric temperature and is also a constant fraction of the number required for complete absorption.

abundance of elements, it has been assumed that the distribution of elements in stellar atmospheres is roughly the same as it is in the first ten miles of the earth's crust. F. W. Clarke¹⁰ from the means of numerous analyses has given and recently revised¹¹ the percentage abundance *by weight* of the thirty-one most abundant elements in the first ten miles of the earth's crust. What is here desired is the percentage abundance *by atoms*, which may be obtained from Clarke and Washington's¹¹ figures by dividing by the respective atomic weights and reducing to percentages. In Table 17 the thirty-one elements are arranged in order of abundance by atoms with the percentages by weight and by number of atoms following. It is assumed then as a first approximation to the truth that the value of a in equation (2), is the percentage abundance of atoms in the third column of Table 17. The value of x , the fraction of once ionized atoms is computed for a given temperature T from a modified form of Saha's equation (1). The modification is due to Russell¹², and is to take account of the electron products from atoms other than those of the element under consideration. The effective pressure P_1 is taken as 1 atmosphere and

TABLE 17—RELATIVE ABUNDANCE OF ELEMENTS IN EARTH'S CRUST

Element	% Weight	% Atoms	Element	% Weight	% Atoms	Element	% Weight	% Atoms
Oxygen	49.19	54.940	Chlorine	0.228	0.1149	Nickel	0.030	0.0091
Silicon	25.71	16.235	Phosphorous	0.142	0.0818	Strontium	0.032	0.0065
Hydrogen	0.872	15.459	Sulphur	0.093	0.0518	Cerium, Yttrium	0.019	0.0030
Aluminium	7.50	4.946	Nitrogen	0.030	0.0383	Copper	0.010	0.0028
Sodium	2.61	2.028	Manganese	0.108	0.0351	Beryllium	0.001	0.0020
Calcium	3.37	1.503	Fluorine	0.030	0.0282	Boron	0.001	0.0016
Iron	4.68	1.485	Chromium	0.062	0.0213	Zinc	0.004	0.0011
Magnesium	1.94	1.426	Vanadium	0.038	0.0133	Cobalt	0.003	0.0009
Potassium	2.38	1.088	Lithium	0.005	0.0129	Lead	0.002	0.0002
Titanium	0.648	0.2407	Barium	0.075	0.0098			
Carbon	0.139	0.2066	Zirconium	0.048	0.0095			

the value of x computed for lithium for the various temperatures. The value of x for other elements with different ionization potentials is then calculated from Russell's¹² equation (6) viz., $\frac{x_1}{1-x_1} = \frac{K_1}{K_2} \cdot \frac{x_2}{1-x_2}$.

In equation (2) everything can now be computed except the value of K . In order to determine this constant, which physically means about 10/9ths of the number of atoms per sq. cm. column of an element of percentage abundance unity, it is sufficient to use the disappearance of an arc line of an element of known ionization potential in a star whose temperature has been spectrophotometrically determined. Russell¹² has shown that in the sun, temperature 6000° K, the line 6707.85 ($1\sigma - 1\pi$ of lithium whose I.P. is 5.362 volts¹) has disappeared. Saha⁹ is the authority for the statement that in B8 stars, average temperature Wilsing, Scheiner and Münch¹³ 10,400° K, the line 4226.73 ($1S - 1P$ of calcium whose I.P. is 6.087 volts⁴) has disappeared. Performing the necessary computa-

tions and noting that a for lithium from Table 17 is 0.0129 and x at 6000°K is 0.1646 there results from (2)

$$\frac{8.913 \times 10^7}{2.925 \times 10^{-12}} = K (0.0129) (1 - 0.1646) \quad \text{or } K = 2.83 \times 10^{20}$$

Similarly for calcium whose $a = 1.503$ and whose x at $10,400^\circ \text{K}$ is 0.8900

$$\frac{7.697 \times 10^7}{4.647 \times 10^{-12}} = K (1.503) (1 - 0.8900) \quad \text{or } K = 1.00 \times 10^{20}$$

Of course theoretically K is a constant and the uncertainty in values here is due to the uncertainty in the actual abundance of elements in the stars. In what follows the value $K = 1.5 \times 10^{20}$ has been adopted which gives more weight to calcium than to lithium. Equation (2), therefore, becomes

$$b = 1.5 \times 10^{20} a (1 - x) \quad \dots\dots (3)$$

An interesting and an important test of the value of these considerations on the relative abundance of elements is afforded by the behaviour of barium and sodium in the sun, a matter which has recently been discussed by Russell¹⁴. Barium with an I.P. of 5.188 volts⁴ has the line 5535.53 (1S - 1P) absent or excessively faint in the sun and the line 3071.59 (1S - 2P) just present. Sodium, on the other hand, with the smaller I.P. of 5.111 volts⁴ has the well known D lines (1 σ - 1 π) excessively strong in the sun. To account for this Russell¹⁴ has advanced a very ingenious *ad hoc* hypothesis which requires the photospheric radiation to play the rôle of a partial ionizing agent, and assumes that recombination of a free electron and a once ionized atom is less likely to take place when the atom has its electron in an orbit other than 1S. Now if equation (3) be applied to the question and the value of a , the relative abundance of barium in the sun, be computed from the disappearance of 5535 and 3071, the following values result.

$$\frac{1.034 \times 10^7}{3.547 \times 10^{-12}} = 1.5 \times 10^{20} a (1 - 0.2159) \quad \text{or } a = 0.0148 \text{ for disappearance of } 5535.53.$$

$$\frac{2.827 \times 10^6}{6.397 \times 10^{-12}} = 1.5 \times 10^{20} a (1 - 0.2159) \quad \text{or } a = 0.0038 \text{ for disappearance of } 3071.59.$$

From Table 17 the relative abundance of barium on the earth is 0.0098. In short the disappearance of barium in the sun is precisely what would be expected when its probable relative abundance in the sun is considered. Similarly if the relative abundance of sodium, viz., $a = 2.028$ be taken from Table 17, and the temperature at which D_2 ought to disappear be computed, the following results are obtained:—

$$\begin{aligned} \text{At } 10,000^\circ \text{K} : b &= \frac{4.944 \times 10^7}{3.336 \times 10^{-12}} = 1.482 \times 10^{19} : \text{R't side of (3)} = 1.5 \times 10^{20} \times 2.028 \\ (1 - 0.9460) &= 1.643 \times 10^{19} \end{aligned}$$

$$\begin{aligned} \text{At } 10,400^\circ \text{K} : b &= \frac{5.459 \times 10^7}{3.336 \times 10^{-12}} = 1.636 \times 10^{19} : \text{R't side of (3)} = 1.5 \times 10^{20} \times 2.028 \\ (1 - 0.9600) &= 1.217 \times 10^{19} \end{aligned}$$

Accordingly if the relative abundance of sodium in the earth and in the sun is approximately the same, then the D lines should not disappear until the stellar type B8 is reached, and should, therefore, appear of great strength in the sun. In short the relative abundance of elements, which is a necessary extension of Saha's theory, accounts automatically for

the behaviour of barium and sodium in the sun.* Furthermore it will account (see sec. 7) for other "anomalous" cases, such as the persistence in O-type stars of the Balmer lines after Mg+4481 and the He arc lines have disappeared, cases which Russell's hypothesis might have difficulty in meeting.

SECTION C—CAUSES OF IONIZATION AND THE ELECTRON COLLISION HYPOTHESIS

The validity of the conclusions drawn from Saha's theory as to the physical conditions in stars must rest in turn on the validity of the assumptions on which the theory is based. Three of these assumptions may be noted. (1) In his original presentation Saha effectively assumed that atoms of a given element could only recombine with free electrons dissociated from themselves. Milne¹⁵ and Russell¹² pointed out this error and Russell¹² has derived modified formulæ (used in this paper) to take account of the free electrons from all the chromospheric atoms. (2) Saha has assumed that the rate of recombination of free electrons and ionized atoms upon encounter is independent of the temperature. However, it is probable that as the velocity of thermal agitation increases with the temperature so will the chances of recombination on encounter diminish. In fact it has been shown by Phillips¹⁶ that the coefficient of recombination diminishes very rapidly with temperature. (3) Finally Saha has not indicated the physical processes by which ionization takes place, and has assumed that in some undefined manner the energy for the ionization is drawn from the medium. This question of the causes of ionization is of such importance as to merit further consideration.

Radiation from the photosphere and collisions with high velocity free electrons are two causes of ionization that must be at work in stellar atmospheres. The strong absorption in A-type stars at a probable temperature of 10,000° K of the Balmer lines, the mechanism of whose production is clearly understood, affords a not unfair test of the relative importance of these two causes. While, it is true that the resonance wave length of hydrogen lies in the far ultra violet (1216 Å), yet in that respect the hydrogen atom does not differ from any of the once ionized atoms or from the neutral helium atom. To account for the strong Balmer lines in A-type stars is, therefore, a particularly appropriate test of the relative importance of these two causes of ionization in high temperature stars such as those comprised within the Harvard types A, B, O.

In order that a hydrogen atom may absorb lines of the Balmer series the electron must be lifted from its normal 1 quantum to the 2 quantum orbit. Absorption of photo-

*Prof. Russell has drawn my attention to the fact that there is in the case of barium a further unexplained anomaly. If the arc spectrum of barium disappears when the fraction of neutral atoms, $1-x$, is 0.78 approximately, then the spark spectrum of barium will not appear since the fraction of once ionized atoms is only 0.22. But Russell has shown (*Ap. J.* 55, 354) that the spark spectrum of barium is present in the sun. He has pointed out to me that if a pressure of 10^{-3} or 10^{-4} atmospheres (which recent investigations of his indicate) be assumed, then this anomaly will disappear. For with this pressure the fraction of neutral atoms will only be 0.02 while of once ionized atoms there will be 0.98. So that while the arc spectrum of barium will disappear at 6000°K if the relative abundance of the element is of the order of 0.007 the spark spectrum will be very conspicuous. It should be noted that this difficulty does not occur in the electron collision hypothesis developed in Sec. C. For this theory the fraction of neutral barium atoms is only 0.24 at 6000° K and of once ionized atoms 0.76. So that while the arc lines will disappear on this theory if the relative abundance is of the same order as on the earth, the spark lines will persist.

spheric radiation of the appropriate wave length (1216 Å), or collision with a free electron with a velocity greater than 10.16 volts will lift the electron to the 2 quantum orbit. An upper limit to the number of H atoms brought into the 2 quantum condition by *radiation from the photosphere* can be readily calculated. The amount of energy radiated per sq. cm. per sec. by the photosphere at any given temperature and wave length can be computed from Wien's law $E\nu d\nu = \frac{2\pi h\nu^3}{c^2} e^{-h\nu/kT} d\nu$. As the hydrogen atoms are moving with their velocities of thermal agitation, they can absorb radiation in a wide range of frequencies; $d\nu$ has, therefore, been taken as varying from 7.61×10^{10} for $H\alpha$ to 5.33×10^{11} for 938 Å, corresponding to a range in atomic velocities of ± 25 km. In the accompanying schedule there are computed the total number of atoms which will have their electrons lifted to the 2, 3, 4, 5, 6, and from 7 to ∞ quantum orbits by the absorption of photospheric radiation. Of those atoms which have their electrons lifted to orbits higher than the 2 quantum only a small fraction will resume the 2 quantum state. Assuming, however, that all these atoms reach this state, then the sum of the numbers in the last column of the schedule gives an upper limit to the total number of H atoms with their electrons brought to the 2 quantum orbit by photospheric radiation. This upper limit is 1.079×10^{18} per sq. cm. column in the stellar atmosphere per sec. Assuming further that these atoms only absorb $H\alpha$, each atom of course absorbing from the quantum relation 2.994×10^{-12} ergs, then the total amount of $H\alpha$ energy absorbed will be 3.231×10^6 ergs per sq. cm. column per sec. But at $10,000^\circ$ K each sq. cm. of the photosphere radiates per sec. of $H\alpha$ radiation (± 25 km = ± 0.55 Å) 4.225×10^7 ergs. Accordingly under the most favourable conditions to photospheric radiation as the cause of ionization, the ratio of the intensities $H\alpha$ absorption line: continuous spectrum will be 1 : 1.085. Wedge spectra of α Cygni taken here indicate that actually the Balmer absorption lines are less than one-thousandth of the intensity of the neighbouring continuous spectrum. It is evident, therefore, that radiation from the photosphere plays, in the production of the Balmer lines and probably of all enhanced lines in early type stars, an insignificant role.

Electron lifted from	Energy required per atom ergs	Radiation required to lift electron	Energy of this radiation in ergs per sq. cm. per sec.	No. of atoms partially ionized
1 - 2	1.617×10^{-11}	N ($1 - \frac{1}{4}$) : 1216 Å	2.156×10^6	1.333×10^{17}
1 - 3	1.916	N ($1 - \frac{1}{9}$) : 1026	4.799×10^5	2.504×10^{16}
1 - 4	2.021	N ($1 - \frac{1}{16}$) : 972	2.769×10^5	1.370×10^{16}
1 - 5	2.069	N ($1 - \frac{1}{25}$) : 950	2.137×10^5	1.033×10^{16}
1 - 6	2.096	N ($1 - \frac{1}{36}$) : 938	1.856×10^5	8.855×10^{15}
1 - 7	2.111×10^{-11}	N ($1 - \frac{1}{49}$) - N	1.875×10^7	8.882×10^{17}
1 - ∞)		931 to 911 Å		

On the other hand it may be shown that collisions with free electrons, moving with their velocities of thermal agitations, will produce the observed Balmer lines in A-type spectra. In order to arrive at any estimate of the amount of ionization produced by

electron collisions, it is necessary to make some assumptions as to the probable concentrations of hydrogen atoms and electrons. From Richardson's¹⁷ formula for thermionic emission $N = AT^{1/2}e^{-b/T}$ where N is number of electrons emitted per unit area per unit time at temperature T and the average values of $A = 5 \times 10^{25}$, $b = 5 \times 10^4$ are taken, the number of free electrons per cu. cm. at $10,000^\circ \text{K}$ in the chromosphere should be 2×10^{13} . As at 6000°K the Zeeman effect¹⁸ in sun spots requires between 10^{17} and 10^{18} free electrons per cu. cm., it is not unreasonable to suppose there are 10^{13} free electrons per cu. cm. at $10,000^\circ \text{K}$. Further assuming there are only 10^{13} hydrogen atoms per cu. cm. in the stellar atmosphere (less than there are in the earth's atmosphere at a height of 200 km), then it is possible to compute the number of collisions per cu. cm. per sec. between the free electrons and the hydrogen atoms. From the kinetic theory of gases¹⁹ the number of collisions will be $n_1 n_2 S_{12}^2 \sqrt{2\pi kT \left(\frac{1}{m_1} + \frac{1}{m_2} \right)}$ where n_1, n_2 are the number of free electrons and hydrogen atoms respectively, S_{12} is the distance between the centres of an electron and a hydrogen atom on collision ($0.53 \times 10^8 \text{ cms}$), k is the Boltzman gas constant, T the temperature and m_1, m_2 the masses of the free electron and hydrogen atom respectively. Accordingly at $10,000^\circ \text{K}$ there will be 5.56×10^{22} collisions per cu. cm. per sec. between the 10^{13} electrons and 10^{13} hydrogen atoms. This is the minimum number because actually the charge on the electron will bring about impacts that otherwise would not take place. Now when a free electron is travelling with a velocity between $1.895 \times 10^8 \text{ cms. per sec.}$ (10.16 volts) and $2.063 \times 10^8 \text{ cms. per sec.}$ (12.04 volts) it will have sufficient kinetic energy to lift the hydrogen electron from the normal 1 quantum to the 2 quantum orbit. It is possible to compute from the kinetic theory of gases²⁰ the fraction of electrons at $10,000^\circ \text{K}$ whose velocities of thermal agitation lie between these two limits. Its value is 2.61×10^{-5} . Accordingly of the 5.562×10^{22} collisions per cu. cm. per sec. between electrons and hydrogen atoms, the fraction 2.61×10^{-5} , or in all 1.45×10^{13} , will take place between hydrogen atoms and these high velocity electrons. Even if only 1 in 10^6 of these collisions is effective in lifting the hydrogen electron to the 2 quantum orbit, there will still be 1.45×10^{12} hydrogen atoms per cu. cm. per sec. in a condition to absorb the Balmer series. This will require of course that a number of these 1.45×10^{12} atoms have been partially or completely ionized several a second. As, however, recent work of Stark²¹ and Wood²² indicates that the time interval between partial ionization and return to the normal lies between 10^{-4} and 10^{-7} secs., this requirement offers no difficulty. In a sq. cm. column 1,000 km. high, in which the maximum chromospheric absorption may be supposed to take place, there will then be $1.45 \times 10^{12} \times 10^8 = 1.45 \times 10^{20}$ hydrogen atoms in a condition to absorb the Balmer lines. It is to be noted here that the pressure of the chromosphere has been effectively assumed in computing the number of collisions to be 1/10th of an atmosphere. If the pressure is less than this while the number of effective collisions per cu. cm. will be smaller, yet the chromosphere will be correspondingly thicker so that an estimate of 10^{20} partially ionized hydrogen atoms per sq. cm. column per sec. is probably not far out. The number of atoms necessary for the complete absorption of a given line can be found by dividing the photospheric radiant energy of that wave length by the amount of energy absorbed by a single atom of

that wave length. In this way at $10,000^{\circ}$ K the numbers of H atoms per sq. cm. column per sec. with their electrons in the 2 quantum orbit required for complete absorption of the following lines are

$$\begin{aligned} \text{H}\alpha & 4.225 \times 10^7 / 2.994 \times 10^{-12} = 1.411 \times 10^{19} : \text{H}\beta \quad 6.137 \times 10^7 / 4.042 \times 10^{-12} = 1.518 \times 10^{19} \\ \text{H}\gamma & 6.650 \times 10^7 / 4.527 \times 10^{-12} = 1.469 \times 10^{19} : \text{H}\delta \quad 6.853 \times 10^7 / 4.789 \times 10^{-12} = 1.431 \times 10^{19} \\ \text{H}\epsilon & 6.929 \times 10^7 / 4.949 \times 10^{-12} = 1.400 \times 10^{19} \end{aligned}$$

The total number of atoms for *complete* absorption of the first five lines of the Balmer series, viz., 7.23×10^{19} , is less than the number 10^{20} probably furnished by electron collisions, even when that cause of ionization is given a numerically unfavourable treatment. The contrast between the two causes of ionization, radiation from the photosphere and electron collisions, is thus most marked, and it is probably safe to conclude that electron collisions play an important role in the ionization of stellar atmospheres.

Milne¹⁵ and Anderson²³ have drawn attention to the fact that the use of the law of mass action by Saha in formulating his ionization theory implicitly assumes that collisions with free electrons do not play any part in ionization. From the preceding discussion this implicit assumption does not appear to be justified. In view of the uncertainty of this assumption, and also of the assumption that the co-efficient of recombination does not vary with the temperature, it is evident that conclusions as to stellar temperatures and the relative abundance of elements drawn from Saha's theory must be treated with caution. Accordingly in order to act as a check on the results given by Saha's theory, an independent hypothesis of ionization by electron collisions based on three more or less plausible assumptions, has been formed.

The three assumptions, upon which this hypothesis of ionization by electron collisions rests, are as follows:—(1) Collisions of atoms with free electrons is the preponderating cause of ionization. (2) Ionization takes place on single impact; cumulative effects, as discussed by K. T. Compton²¹, are of secondary importance. (3) Recombination of a once ionized atom and a free electron only takes place when the latter has a velocity corresponding to less than twice the ionization potential. The only justification for the first assumption lies in the preceding discussion on the causes of ionization. The question of the relative importance of single impacts and cumulative effects, the subject of the second assumption, has been discussed with great care by Compton²⁴. Ionization by single impact takes place when an electron travelling with the ionization potential velocity completely removes the atomic electron. Ionization by multiple impact takes place when the atomic electron is removed to the 1P orbit by a free electron with the resonance velocity and before the atom can resume its normal condition, a second impact with a free electron (velocity = ionization minus resonance velocity) completely removes the atomic electron. This form of cumulative effect Compton²⁵ has shown to be of negligible importance. If, however, the atom resumes its 1 S state before a second impact can take place, then there will be emitted 1 quantum of monochromatic radiation. The absorption of this quantum of radiation by a neighbouring normal atom will partially ionize it. In this way by a process of radiation transfer Compton points out that there should be a large number of atoms in a partially ionized condition, so that impact with an electron with less than the ionization velocity will result in complete ionization of the atom. Under

laboratory conditions, monochromatic gases at relatively high pressures and subjected to dense electron bombardments show very pronounced cumulative effects due to this process of radiation transfer. Thus an arc can be struck in helium and maintained at the resonance voltage²⁴. It is doubtful, however, whether under stellar conditions such cumulative effects are of importance. On the one hand the number of high velocity electrons is so small as to be far removed from the conditions that laboratory experience has shown to be essential for cumulative effects. On the other hand the process of radiation transfer will be greatly hindered by the changes in frequency of the monochromatic radiation produced by the Doppler effects due to the high velocities of the thermal agitation of the atoms. Accordingly the assumption of ionization by single impacts is probably a close approximation to the truth. The third and final assumption has to do with the conditions under which recombination can take place,—a problem of considerable difficulty. Fixing attention for simplicity on the hydrogen atom, in order to remove the atomic electron from the 1 quantum orbit to infinity, the additional kinetic energy of $2\pi^2 m_0 e^4 / h^2$ ergs (corresponding to the ionization potential) must be communicated to it, making the kinetic energy of the electron in all $4\pi^2 m_0 e^4 / h^2$ (=potential energy = twice the ionization potential). If an electron bound to the atom can be removed to infinity when it has this kinetic energy (corresponding to twice the ionization potential), it is probable that a free electron which enters the atomic system with this kinetic energy or greater cannot be retained by the nucleus. Similar considerations apply to more complex atoms and there thus appears to be justification for assuming that recombination can only take place when the electron velocity corresponds to less than twice the ionization potential.

Let n_1 be the number of neutral atoms of the element under consideration per cu. cm., and n_2 the number of free electrons per cu. cm. in the chromosphere at the temperature T . The number of collisions per sec. per cu. cm. between these free electrons and atoms will be proportional to¹⁹ $n_1 n_2 \sqrt{T/m_1}$, where m_1 is the atomic weight of the element. Of these collisions only those which take place between atoms and free electrons travelling with a velocity equal to or greater than the ionization potential, according to the second assumption, will be effective in producing once ionized atoms. At any temperature the fraction of the total number of electrons travelling with any velocity greater than that produced by a potential drop of I volts can be computed. Denoting this fraction by the symbol $E\left(\frac{I}{T}\right)$, its value is given by²⁰ $E\left(\frac{I}{T}\right) = \text{erf } z + 2z/\sqrt{\pi} e^{-z^2}$ where $z = 108.03 \sqrt{\frac{I}{T}}$, and $\text{erf } z = \frac{2}{\sqrt{\pi}} \int_z^\infty e^{-z^2} dz$. Then where A_1 is some unknown constant, the number of ionized atoms produced by electron collisions per cu. cm. per sec. is

$$q_1 = A_1 n_1 n_2 E\left(\frac{I}{T}\right) \sqrt{T/m_1} \dots (4).$$

If n'_1 is the actual number of once ionized atoms present per cu. cm., A_2 is an unknown constant, then from the third assumption the number of recombinations taking place per cu. cm. per sec. will be

$$A_2 n'_1 n_2 \left[1 - E\left(\frac{2I}{T}\right) \right] \sqrt{T/m_1} \dots (5).$$

When a steady state is reached there will be as many atoms recombining as there are new once ionized atoms being formed so that q_1 will be equal to the expression (5). Accordingly n'_1/n , the ratio of once ionized to neutral atoms will be given by

$$\frac{n'_1}{n_1} = \frac{x}{1-x} = A E\left(\frac{I}{T}\right) / \left[1 - E\left(\frac{2I}{T}\right)\right] \dots (6).$$

where x is the fraction of once ionized atoms and A is some unknown constant.

Equation (6), when A is known, thus will give the fraction of once ionized atoms for an element of known I.P. at a given temperature in precisely the same way as equation (1) gives the fraction of ionized atoms on Saha's theory. Again consideration of the relative abundance of elements is necessary and equation (2) $b = K a (1 - x)$ will apply where x in this case is given by (6) and K is an unknown constant. The quantities b and a are of course determined in precisely the same way as explained for Saha's theory. In order to ascertain the values of the constants A and K , the disappearance of lithium 6707.85 in the sun at 6000°K¹² and of calcium 4226.73 in B8 stars at 10,400° K⁹ have been used.

Lithium $E\left(\frac{I}{T}\right) = \text{erf } 3.230 + 1.1284 \times 3.230 / e^{10.443} = 1.1230 \times 10^{-4}$; $E\left(\frac{2I}{T}\right) = 4.582 \times 10^{-9}$

Substituting in (6) and (2) there results $\frac{8.913 \times 10^6}{2.925 \times 10^{-12}} = \frac{0.0129 K}{1 + 1.1230 \times 10^{-4} A}$

Calcium $E\left(\frac{I}{T}\right) = \text{erf } 2.613 + 1.1284 \times 2.613 / e^{6.823} = 3.417 \times 10^{-3}$; $E\left(\frac{2I}{T}\right) = 5.047 \times 10^{-6}$

Substituting in (6) and (2) there results $\frac{7.697 \times 10^7}{4.647 \times 10^{-12}} = \frac{1.503 K}{1 + 3.417 \times 10^{-3} A}$

From these final equations for lithium and calcium there results $A = 2.0 \times 10^4$ and $K = 7.7 \times 10^{20}$. Accordingly the equations for the fraction of ionization and for the disappearance of an arc spectrum on the electron collision hypothesis become

$$\frac{x}{1-x} = 2.0 \times 10^4 E\left(\frac{I}{T}\right) / \left[1 - E\left(\frac{2I}{T}\right)\right] \dots (7); b = 7.7 \times 10^{20} a (1 - x) \dots (8)$$

The theory may be applied as was Saha's modified theory, to investigate the behaviour of barium and sodium in the sun¹⁴. Inserting the necessary ionization potentials and temperatures in (7) and (8), it is found that the barium lines 5535.53 and 3071.59 will disappear at 6000° K if the percentage abundance of the element in the sun lies between 0.0155 and 0.0024. The limits found from Saha's theory were 0.0148 and 0.0038 (Sec. B, Appendix) and the relative abundance on the earth is from Table 17 $a = 0.0098$. Further it is found from the electron collision hypothesis that if the abundance of sodium is the same in the stars as it is on the earth, the D lines will not disappear until a temperature of 9600° K is reached. From Saha's theory the D lines under the same conditions would disappear at about 10,200° K. (Sec. B, Appendix). It will be noted that the electron collision hypothesis, equally with Saha's theory, is thus able to explain the apparently anomalous behaviour of these elements.

Summarizing, the principal results of this appendix have been the development of two methods, Saha's modified theory and the electron collision hypothesis, by the use of which some of the physical conditions in the star can be determined from the disappearance of an arc spectrum of known ionization potential. It should be noted in conclusion that the methods are equally applicable and can readily be extended to *spark spectra*.

For Saha's theory Russell¹² has given the correct formula for computing the ratio of twice ionized to once ionized atoms, namely $\frac{y}{x} = \frac{K'}{K_2} \cdot \frac{x_2}{1-x_2}$ where $\log K = -5036 I/T + 2.5 \log T - 6.5$ and the subscript 2 refers in this paper to lithium with "effective pressure" P_1 taken as one atmosphere. For the electron collision hypothesis where n_1' is the number of once ionized, n_1'' the number of twice ionized atoms present per cu. cm. then in the same manner as was shown before $\frac{n_1''}{n_1'} = \frac{y}{x} = A' E\left(\frac{I'}{T}\right) / \left[1 - E\left(\frac{2I'}{T}\right)\right]$. The value of A' may be readily deduced from the value of A for arc spectra when the effect of the charges born by the free electrons and the once or twice ionized atoms in increasing the number of collisions is considered. A simple manner of treating the matter is to suppose that the charge acts as if it increased the radius of the sphere of influence of the charged particle. Then the effective radius for an electron and a once ionized atom will be βe , for a twice ionized atom $2\beta e$ and the radius of an uncharged atom is assumed to be negligibly small. Recalling that the distance between the centres of particles on collision enters as a square¹⁹, it may then be immediately shown that $A' = (16/9) A = 3.6 \times 10^4$. The resulting expression is then

$$\frac{y}{x} = 3.6 \times 10^4 E\left(\frac{I'}{T}\right) / \left[1 - E\left(\frac{2I'}{T}\right)\right] \dots (9).$$

As the temperature becomes higher, the fraction of neutral atoms becomes vanishingly small and for either Saha's theory or the electron collision hypothesis $x + y = 1 - \epsilon$ where ϵ is a second order quantity. Accordingly for the disappearance of a once enhanced spectrum y/x may be written $y/(1-y)$. From the values of y thus computed, for the Saha theory the abundance formula $b = 1.5 \times 10^{20} a (1-y)$ and for the electron collision hypothesis $b = 7.7 \times 10^{20} a (1-y)$ may be used to determine the temperature at which a spark spectrum will disappear.

In short the two methods are applicable equally to arc or spark spectra. They give from the disappearance of a spectrum of known series relations and ionization potential the temperature of the star if the abundance of the element is known, or the abundance of the element if the stellar temperature is known. As the two methods are based on completely different assumptions, it is probable that the true temperature or abundance will be somewhere near their numerical estimates. Interesting examples of their application and of the accordance of the results which they give will be found in Sec. 7,—“Physical Conditions in O-type Stars.”

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END OF VOLUME I.

DESCRIPTION OF PLATE

- FIG. 1—SINGLE-PRISM SPECTRUM OF 10 LACERTAE WITH IRON ARC COMPARISON TAKEN SEPTEMBER 11TH, 1921. SPECTRUM IN FOCUS FROM $0.39 - 0.67\mu$. MAGNIFICATION $6.5\times$ APPROXIMATELY.
- FIG. 2—TWO-PRISM SPECTRUM OF 9 SAGITTAE WITH IRON ARC COMPARISON TAKEN AUGUST 26TH, 1921. OWING TO CURVATURE OF FIELD SPECTRUM IS ONLY IN FOCUS FROM $0.41 - 0.49\mu$. MAGNIFICATION $6.5\times$ APPROXIMATELY.
- FIG. 3—THREE-PRISM SPECTRUM OF $H\beta$ AND ITS He_+ COMPONENT FROM THE SPECTRUM OF 10 LACERTAE TAKEN AUGUST 12TH, 1921. MAGNIFICATION $8.1\times$ APPROXIMATELY.
- FIG. 4—SINGLE-PRISM SPECTRUM OF $H\delta$, ITS He_+ AND N_+ COMPONENTS FROM THE SPECTRUM OF 10 LACERTAE TAKEN SEPTEMBER 11TH, 1921. MAGNIFICATION $16\times$ APPROXIMATELY.
- FIG. 5—THREE-PRISM SPECTRUM OF $H\gamma$ AND ITS He_+ COMPONENT FROM THE SPECTRUM OF 9 SAGITTAE TAKEN AUGUST 12TH, 1921. MAGNIFICATION $9\times$ APPROXIMATELY.

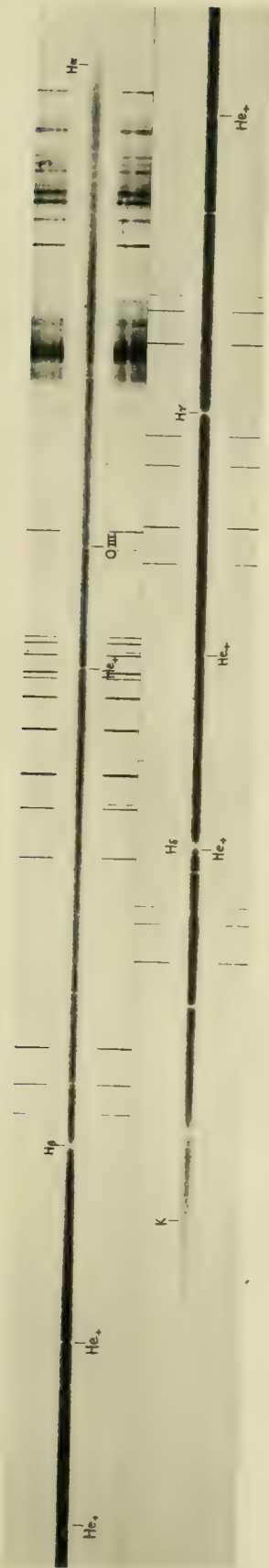


Fig 1

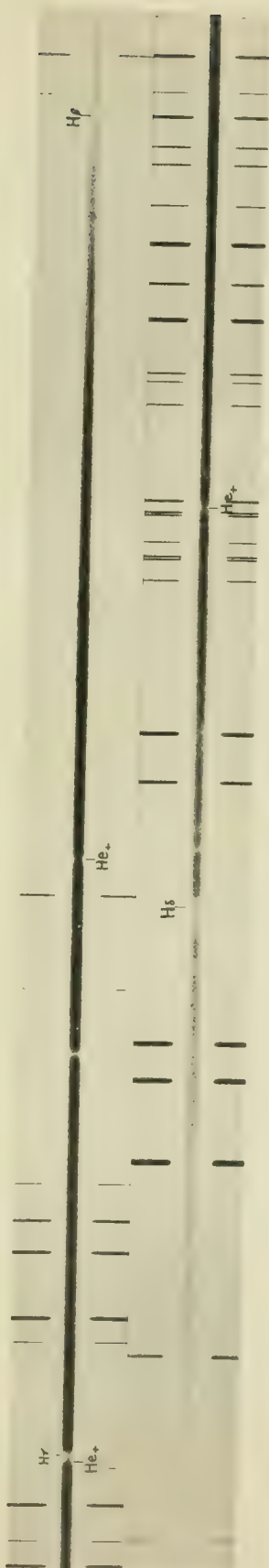


Fig 2.



Fig 3.

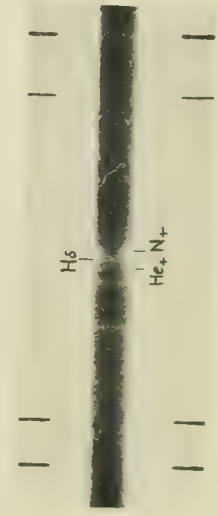


Fig 4.

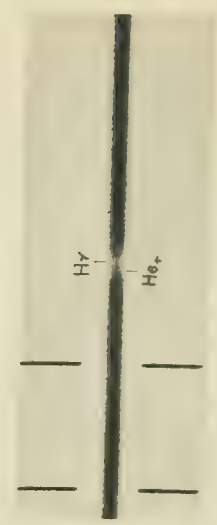
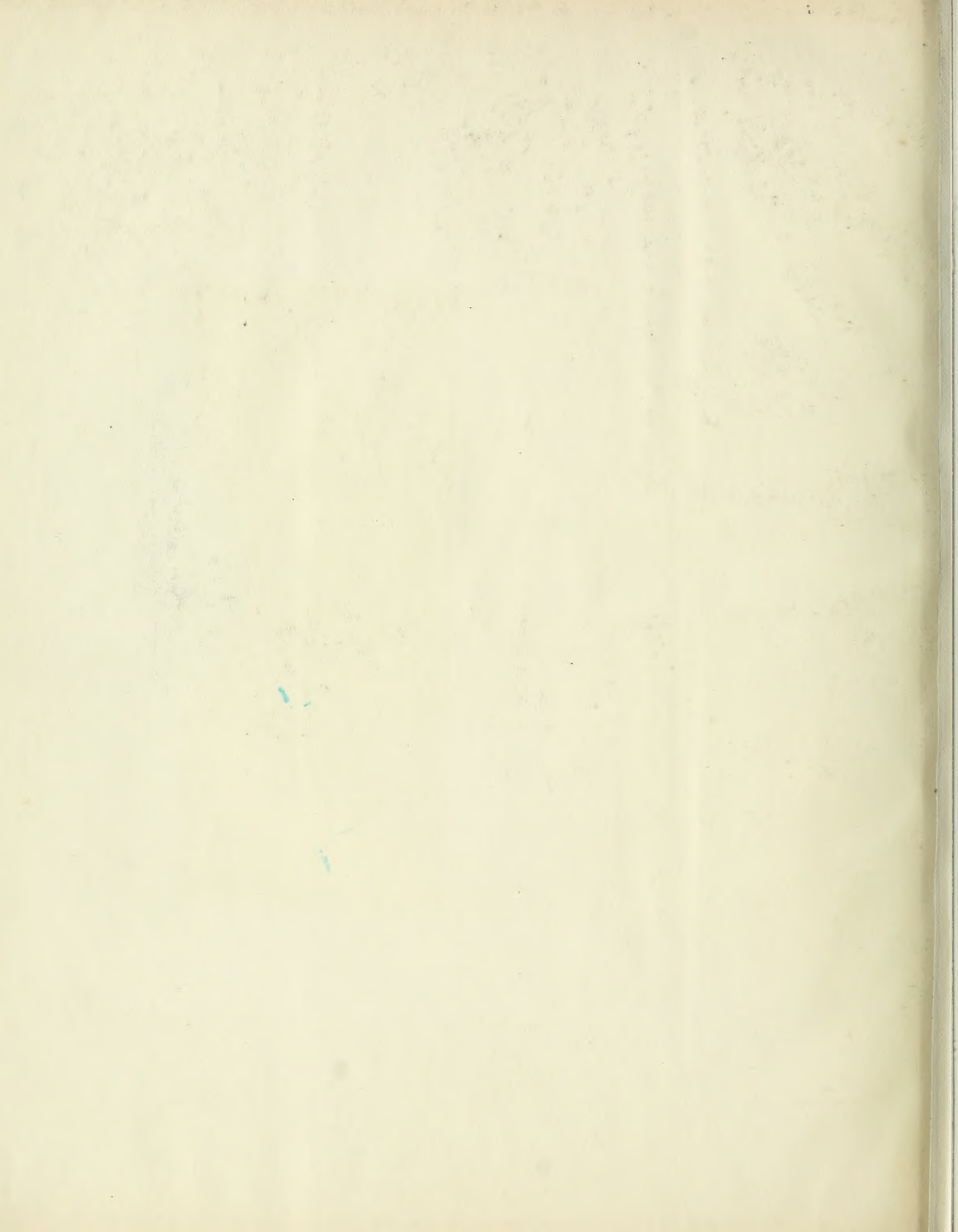


Fig 5.



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